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DIESEL ENGINE ENDURANCE TEST WITH WATER CONTAINING FIRE-RESISTA--ETC(U)
SEP 79 J V MOFFITT, E C OWENS, B R WRIGHT DAAG53-76-C-0003

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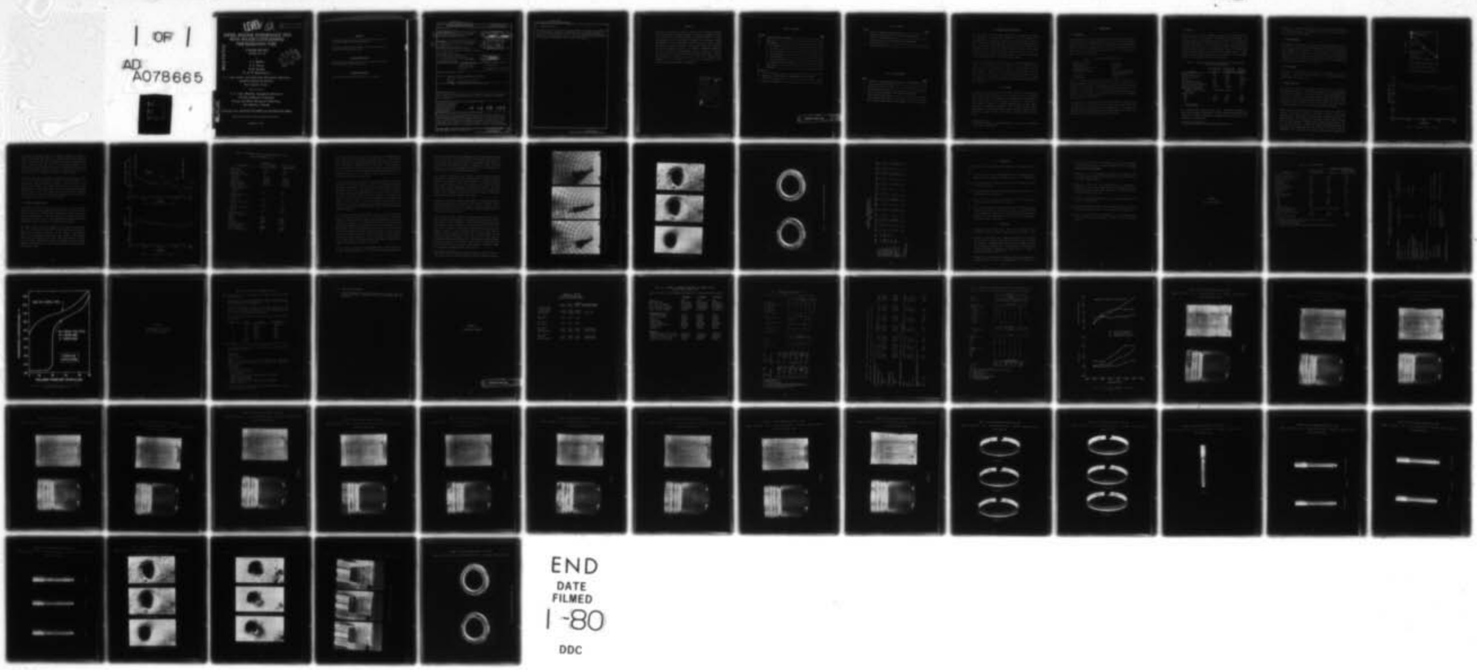

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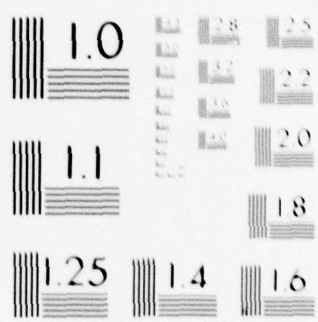


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# DIESEL ENGINE ENDURANCE TEST WITH WATER-CONTAINING FIRE-RESISTANT FUEL

ADA078665



INTERIM REPORT
AFLRL No. 94

by

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Southwest Research Institute
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Under contract to

U. S. Army Mobility Equipment Research and Development Command
Energy and Water Resources Laboratory
Fort Belvoir, Virginia

Contracts Nos. DAAG53-76-C-0003 and DAAK70-78-C-0001



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September 1979

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18. SUPPLEMENTARY NOTES

The research described in this report was conducted between March and May of 1977. Because of unavoidable delays, this report could not be completed until much later.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Water-in-oil Emulsions
Fire-Resistant Fuels
Engine Performance
420-Hour Engine Test
Diesel Engine

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)


A production LDT-465-1C multifuel diesel engine was operated according to a double-length Army/CRC Wheeled Vehicle Test Cycle (420 total hours) using a fire-resistant diesel fuel containing 10 vol% water. The effects of this water-in-fuel *macroemulsion* on engine power output, deposits, wear, and oil degradation were examined. The results indicate that this fire-resistant fuel formulation, under the conditions evaluated, does not result in abnormal


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20. ABSTRACT (cont'd)

deposits nor are there any major effects (adverse or favorable) on engine wear or oil degradation. However, a significant loss in horsepower output as a function of test duration did result. Post-test examinations indicated the presence of fuel-origin deposits in the injection system which were attributed to the sugar-type surfactants used in this investigation.

# FOREWORD

This work was conducted at the U.S. Army Fuels and Lubricants Research Laboratory located at Southwest Research Institute, San Antonio, Texas, under Contracts Nos. DAAG53-76-C-0003 and DAAK70-78-C-0001. The work was sponsored by U.S. Army Mobility Research and Development Command (USAMERADCOM), Fuels and Lubricants Division, Energy and Water Resources Laboratory, Ft. Belvoir, Virginia. The project monitor and Contracting Officer's representative was Mr. F.W. Schaekel, USAMERADCOM, DRDME-GL, Ft. Belvoir, Virginia. Acknowledgement is given to Messrs. D.C. Babcock and L.D. Sievers for supervising laboratory and engine tests. Special acknowledgement is given to Messrs. M.E. LePera, F.W. Schaekel, R.D. Quillian, Jr., A.A. Johnston, S.J. Lestz, and F.M. Newman for their participation, encouragement, and suggestions.

TABLE OF CONTENTS



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## LIST OF TABLES



## LIST OF ILLUSTRATIONS

# I. INTRODUCTION AND BACKGROUND

In recent years, laboratories have been conducting research to determine the attributes of burning water emulsions in diesel engines.[(1-5)*] Unfortunately, no unequivocal answer has yet been obtained, primarily due to the numerous parameters that affect the overall performance of the water-containing fuel. Variables such as injection characteristics, compression ratio, combustion chamber design, and size of the water droplets may all be important. These parameters are only some of the more obvious ones; there are undoubtedly many more that may be important to the overall performance of the engine/fuel system.

To add to the difficulty of the evaluation, the water-containing fuel is itself a very complex system. The chemical type and amount of surfactant can have as pronounced an effect on fuel performance as the water content. Studies have shown that the fuel and water chemical compositions may also affect the final emulsion, which would affect the fuel behavior in the engine. At the time of this work (1977), a systematic approach to the overall problem of water-in-fuel emulsions had not been undertaken.

# II. OBJECTIVE

The objective of this study was to further evaluate the feasibility of using water-in-fuel emulsions as fire-resistant fuels by determining their effects on overall performance in an engine that has wide usage in the military fleet. For this program, "performance" is interpreted as those factors affecting total engine operation such as power output, specific fuel consumption, durability of the engine structure (wear), and durability of the fuel-handling system. The basic engine configuration was to remain as close to its factory-produced condition as possible.

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* Superscript numbers in parentheses refer to the list of references at the end of this report.

## III. EXPERIMENTAL

### A. Test Engine

The engine used in this test program was the LDT-465-1C, a six-cylinder, 7.83-liter (478 $in^3$) turbocharged diesel engine using the MAN combustion chamber design. This engine family has wide military field application. With this particular configuration, it is the primary powerplant for the Army's family of 2½-ton tactical trucks. Table 1 lists the general characteristics of the engine.

TABLE 1. LDT-465-1C ENGINE CHARACTERISTICS

| | |
|---|---|
| Number of Cylinders | 6 |
| Bore, cm(in.) | 11.58(4.56) |
| Stroke, cm(in.) | 12.37(4.87) |
| Displacement, liters ($in^3$) | 7.83(478) |
| Compression Ratio | 22:1 |
| Fuel Injection System | Bosch Rotary Distributor w/Density Compensation |
| Turbocharger | 3-in. Schwitzer |
| Piston Type | Annulus |

The fuel injection pump used with this engine family is equipped with a density compensator which varies the full rack fuel delivery rate as a function of fuel viscosity. This system could adjust the full rack fuel delivery rate improperly due to the different viscosity-density relationship of the emulsion. The rack stop was adjusted with neat fuel to give 66.5 to 67.0 pounds per hour fuel delivery rate. This adjustment was not changed for the emulsion.

This engine was equipped with fuel filters designed to separate water from the fuel. An initial brief test of this filter system showed that some water was being removed from the macroemulsion. To circumvent this problem, the fuel filters were removed from the engine, and the fuel was filtered prior to being blended to form the emulsion.

## B. Test Fuel

The fuel used in this test (Appendix A) comprised 88 vol% Reference No. 2 diesel fuel*, 2 vol% surfactant (emulsifier), and 10 vol% water. The surfactant used in this study consisted of a mixture of two proprietary sugar-type substances, a sorbitan fatty acid ester, and a substituted sorbitan fatty acid ester. The resulting emulsion displayed the milky appearance characteristic of a macroemulsion. Table 2 is a compilation of data obtained on the neat fuel and the water-containing fuel. Major changes in the existent gum are due to the residue of the surfactant. However, no other major differences were observed.

TABLE 2. SUMMARY OF PROPERTIES OF WATER-IN-FUEL FIRE-RESISTANT DIESEL FUEL MACROEMULSIONS

| Property | Neat Reference No. 2 Diesel Fuel | 10% Water and 2% Surfactant in Diesel Fuel | Change Caused by Added Phase |
|---|---|---|---|
| Pour Point, °C | -2 | -2 | 0 |
| Specific Gravity (16°C) | 0.86 | 0.88 | +2% |
| Existent Gum, mg/dl | 7 | 1418 | +1411 |
| Ash, wt% | 0.001 | <0.003 | + <0.002 |
| Carbon Residue, wt% | 0.2 | 0.4 | +0.2 |
| Total Acid No. mg KOH/g | 0.04 | 0.16 | +0.12 |
| Accelerated Stability, mg/dl | 0.8 | 2.1 | +1.3 |
| Copper Corrosion Rating | 1A(NIL) | 1A(NIL) | --- |
| NACE TM-01-72 Pipeline Corrosion Rating with SAE 1018 Steel | C (Red Rust) | A(NIL) | --- |
| Viscosity, cSt | | | |
| 77°C | 1.75 | 2.38 | +36% |
| 38°C | 3.47 | 4.75 | +37% |
| 0°C | 10.3 | 14.5 | +41% |
| -2°C | 11.2 | 16.1 | +44% |

## C. Test Lubricant

The lubricant used during the test was a MIL-L-2104C reference oil which had performed satisfactorily in this engine and test cycle previously.(6) Condition comparisons throughout this report will be with the earlier 210-hour test.

* Federal Test Standard 791B, Method 341.4, Section 4.1.

Because of the doubling of the test length from the normal 210 hours, an oil change was made at the midpoint of the test. Thus, the used oil data are for 210-hour durations.

## D. Instrumentation

The engine was loaded by a 225-horsepower dynamometer, which was cradled, and the torque reaction was measured by an electronic load cell. Fuel consumption was measured by a mass flowmeter directly in pounds of fuel per hour. The flowmeter corrects for changes in fuel density and temperature and was found to be accurate with both the neat and emulsified fuels. Oil consumption was measured by draining and weighing the oil daily and adding makeup oil as required.

## E. Cetane Number

The effect of the addition of water on the cetane number of the fuel is presented in Figure 1, where the effects of the surfactants alone on cetane number can also be seen.

## F. Engine Operation

The engine was run-in and operated according to the test procedure described in Appendix B. For comparison purposes, the fuel was switched from the water emulsion to the neat diesel fuel at approximately each 100 hours of operation so that comparisons of power and exhaust emissions could be made. These periods of operation with the neat fuel were short (less than 45 minutes) and should not influence the test results. A complete summary of the test results is included in Appendix C.

Almost immediately upon starting the engine test period, the engine fuel delivery rate began to decrease. As shown in Figure 2, this trend continued until approximately 10 hours when a sharp fueling rate decrease occurred. An inspection of the fuel injection pump indicated that the pump appeared to behave normally except for the change in the full rack delivery rate. Apparently the rack stop adjusting screw had slipped and had reduced the rack stop setting. The fuel setting was readjusted, and no further fuel delivery problems were experienced.

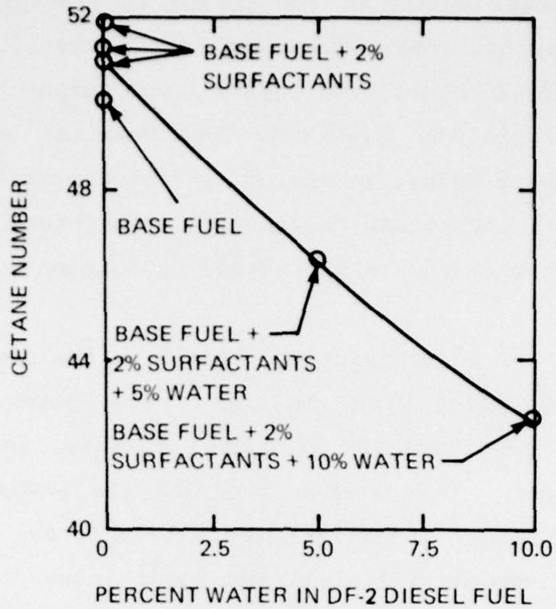


FIGURE 1. INFLUENCE OF FUEL EMULSION INGREDIENTS ON CETANE NUMBER

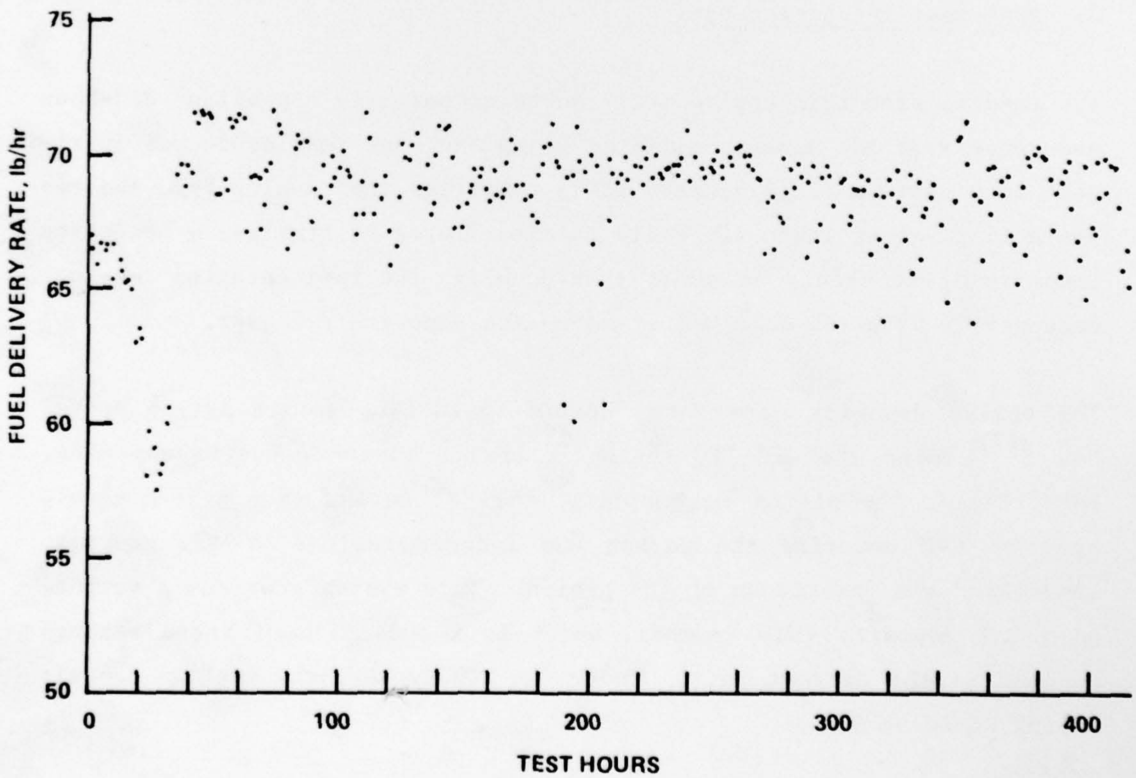


FIGURE 2. FUEL RATE VERSUS TEST HOURS

The observed horsepower output of the engine is presented in Figure 3, where it is obvious that there was a continued loss of power with test time. By the end of 420 hours, the engine power output had decreased by about 16 percent while the fuel rate had remained unchanged. Wear indicators such as wear metals in the oil and blowby rate (Figure 4) did not show any unusual mechanical degradation. Therefore, the power loss may have been due to a change in the actual combustion events.

One event, which may be significant in explaining the power loss, occurred at the 325-hour point when the engine lost power suddenly. The lower power output continued for 12 hours; at this time, two fuel injectors were replaced. This change returned the power output to the previous level. This may indicate potential injection system problems with this fuel and may help explain the power losses noted throughout the test period. The fuel injectors were examined after the test, and the results are included in the ratings section.

G. Post-Test Inspection Data

The results from this engine test can be compared to a previous 210-hour endurance test which was conducted using the same test cycle and lubricant with neat fuel. A summary table comparing the results from the two tests is given as Table 3. While this earlier test provides a basic for comparison, it should be noted that doubling the test duration does not necessarily have the same effect on engine deposits and wear.

The engine deposits were rated according to CRC Deposit Rating Manual No. 1[7], plus the CRC "F" rating[8] of the piston deposits was made. Referring to the piston rating data, the "F" rating is a system developed by CRC covering the carbon and lacquer ratings of the grooves, lands, and the undercrown of the piston. This system provides a weighted total deposits (WTD) number, which is a summation of these ratings rounded to the nearest unit. Under the WTD system, the maximum deposit rating would be 900.

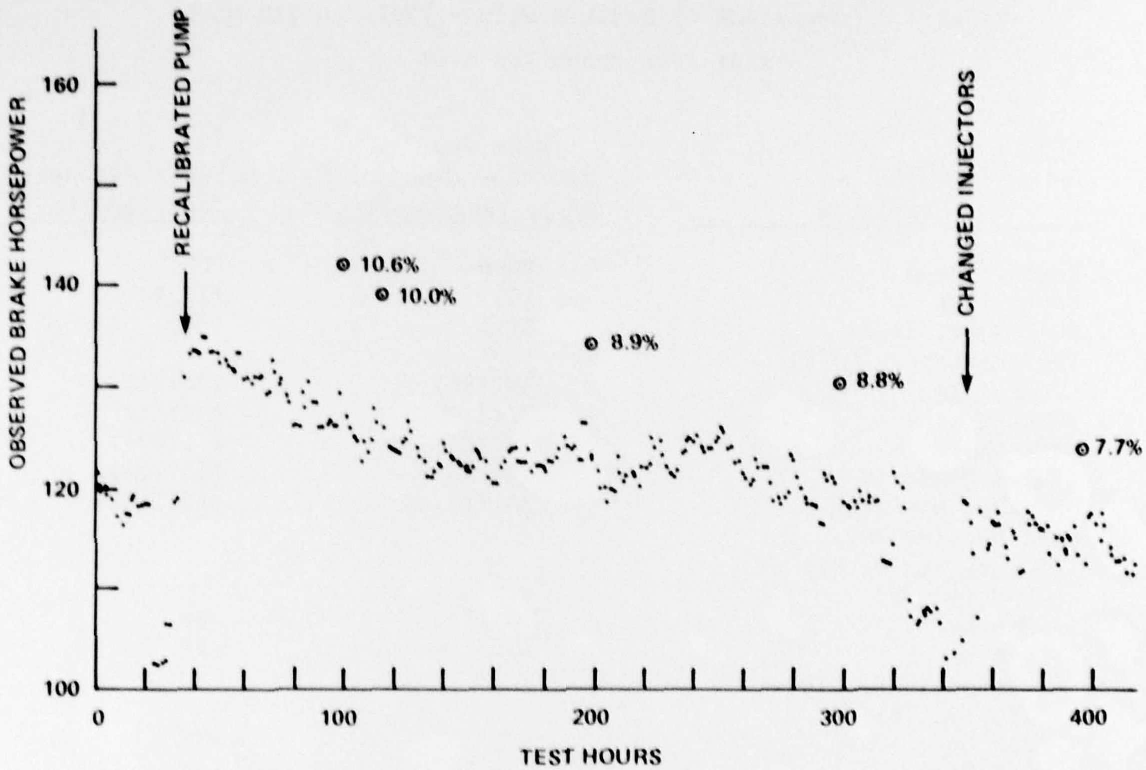


FIGURE 3. HORSEPOWER VERSUS TEST HOURS

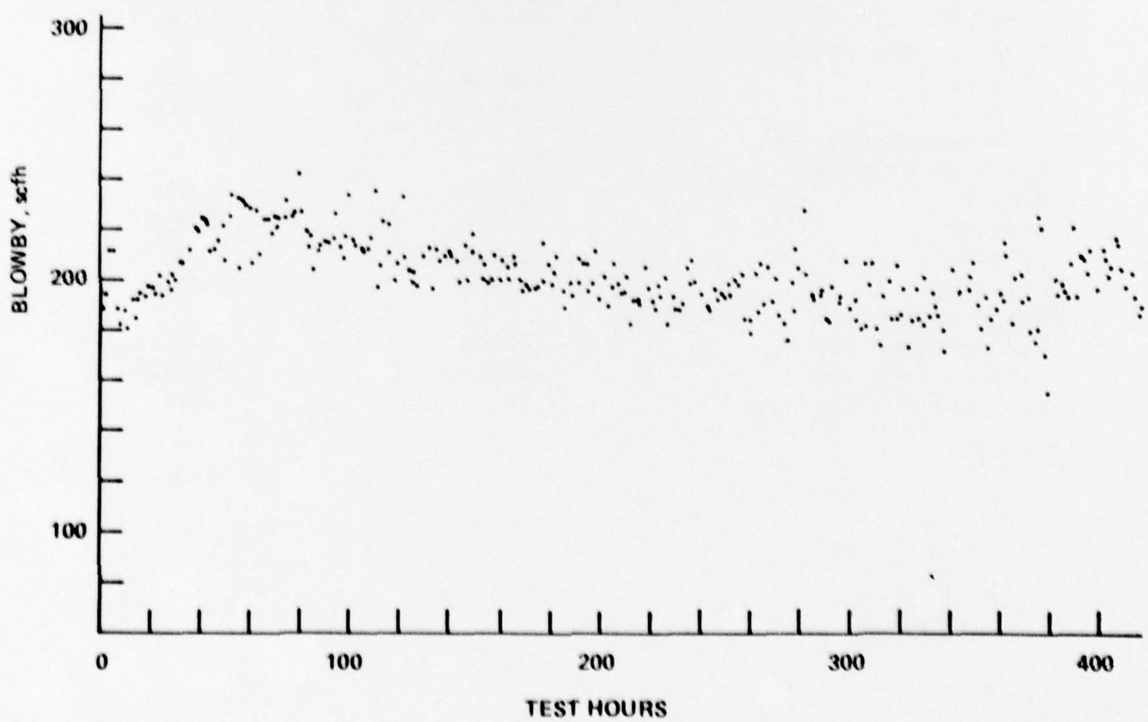


FIGURE 4. BLOWBY VERSUS TEST HOURS

TABLE 3. COMPARISON OF RESULTS WITH REFERENCED 210-HOUR NEAT FUEL ENDURANCE TEST

| Variable | Neat Fuel 210-Hour Tracked Cycle Test Results | Current 420-Hour Test Results |
|---|---|---|
| Engine Speed | 2600 | 2605 |
| Power, Bhp | 140 | 121.2 |
| Fuel Rate, lb/hr | 66.6 | 68.6 |
| Temperatures, °C(°F) | | |
| Jacket In | 69(156) | 77(171) |
| Jacket Out | 81(177) | 83(181) |
| Oil Sump | 114(237) | 111(231) |
| Inlet Manifold | 122(252) | 103(218) |
| Exhaust Manifold | 602(1116) | 611(1132) |
| Used Oil Analysis | | |
| % Change in K. Vis at 38°C (100°F) | | |
| 210 hr | +61 | +57 |
| 420 hr | --- | +48 |
| % Change in K. Vis at 99°C (210°F) | | |
| 210 hr | +40 | +37 |
| 420 hr | --- | +32 |
| Change in TAN (D 664) | | |
| 210 hr | +1.84 | +2.32 |
| 420 hr | --- | +3.45 |
| Change in TBN (D 2896) | | |
| 210 hr | -0.54 | +0.90 |
| 420 hr | --- | +0.14 |
| Wear Measurements, in. | | |
| Change in Ring Gap | | |
| Ring 1 | 0.004 | 0.000 |
| Ring 2 | 0.003 | 0.001 |
| Ring 3 | 0.002 | 0.000 |
| Oil Ring | 0.003 | 0.001 |
| Change in Liner I.D., in. | | |
| 3.81 cm from top | 0.0005 | 0.0032 |
| 7.62 cm from top | 0.0003 | 0.0028 |
| Piston "F" Rating, avg. | 282 | 318 |

The average WTD for the engine was 318, which is not considered excessive. Since the WTD rating with a reference diesel fuel, with only 210 test hours was 282, the piston deposits with the emulsion are reasonable, particularly considering the 420 test hours. Some evidence of ring face burning and vertical scratches was noted along the piston ring face. The deposits in the ring grooves were normal but heavier than the reference test, with 10- to 20-percent ring supporting carbon. All piston rings were free in the grooves.

The pistons themselves had a number of vertical scratches due to carbon particles or other solid materials, while the combustion chamber area had light carbon deposits. The cylinder liners also showed the vertical scratching seen on the rings and piston. Little scuffing occurred, averaging 2 percent, with approximately 25-percent glazing. Rod bearings showed some longitudinal chatter and light wear. In summary, the engine deposits were normal to light, particularly considering the length of the test cycle. Piston and cylinder conditions were considered normal as was the remainder of the engine except for bearings. Because of the chatter and debris embedment noted, the rod bearings were considered marginal.

The cylinder bore wear was significantly greater than that experienced during the 210-hour reference run, but the wear was not considered excessive. This bore wear is particularly interesting when the piston ring wear is examined. In the 210-hour reference run, the average ring wear was approximately 0.003 inches, which is considered average to good wear results. With this emulsion after 420 hours, the ring wear averaged less than 0.001 inch. This tradeoff of cylinder bore versus piston ring wear is unusual and may be related to fuel property effects. However, the wear is nominal for this test duration. Visual inspection of the other areas of the engine such as valve guides, camshaft, etc. showed no apparent wear or unusual conditions.

The fuel injector nozzles were spray checked after test and found to be in good condition mechanically. There was some injector dribble and no

slow bark*, indicating some sluggishness, but the high speed bark was good. One of the nozzles which had been removed during the test had an injector tip hole partially plugged. Such plugging would result in spray pattern degradation and would be expected to result in engine power loss. It could have stemmed from residue of the sugar-type surfactants used to form the aqueous macroemulsion.

Spray pattern evaluations of the injectors using the liquid injection technique[9] are shown in Figure 5. Disassembly of the injector nozzles revealed light deposits on the injector pintels. Microscopic examination of the injection hole in the injector tips showed some slight erosion and possible enlargement as illustrated in Figure 6, but there were no major changes which would totally account for the observed power losses. This examination could not reveal the presence or absence of deposits deep within the injector nozzle holes.

Disassembly of the fuel injection pump showed no fuel-related problems, although excessive wear and scoring of the injection advance control ring and mating parts were noted. Figure 7 shows the injector control ring. These components are oil wetted only, and this behavior would not be expected to be fuel related.

Used oil analysis (Table 4) showed no unusual degradation and no accumulation of water in the lubricant. Comparing these results with the base tests shows some minor differences. Since the lubricant was drained and replaced at 210 hours, the used oil data can be viewed as two 210-hour tests. Thus, the actual values from the base test and these data can be compared. Relative to the base diesel fuel test, this test showed an essentially equal change in viscosity and a slight increase in both pentane and benzene insolubles. Also, the total acid number increase was slightly greater with the emulsion. The wear metals analysis showed a 90-percent increase in iron wear, from 90 with DF-2 to an average 168 parts per million with the emulsion. This increase is probably related to the increased cylinder bore wear noted earlier.

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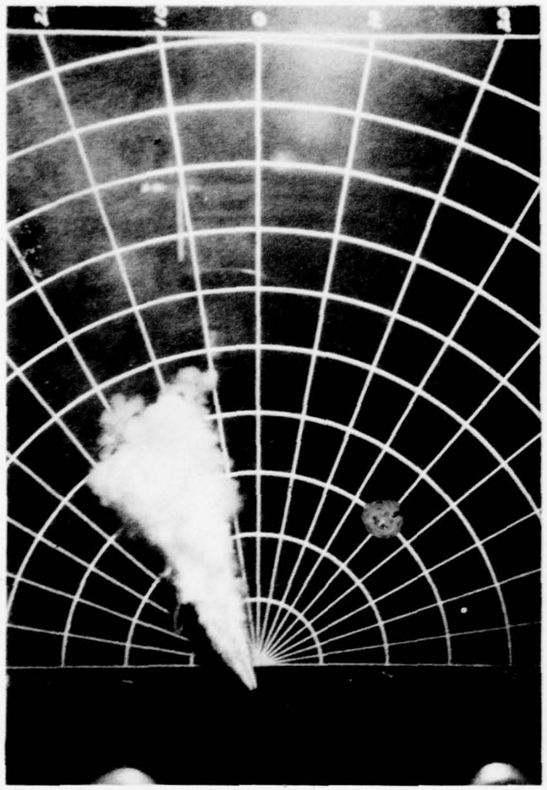
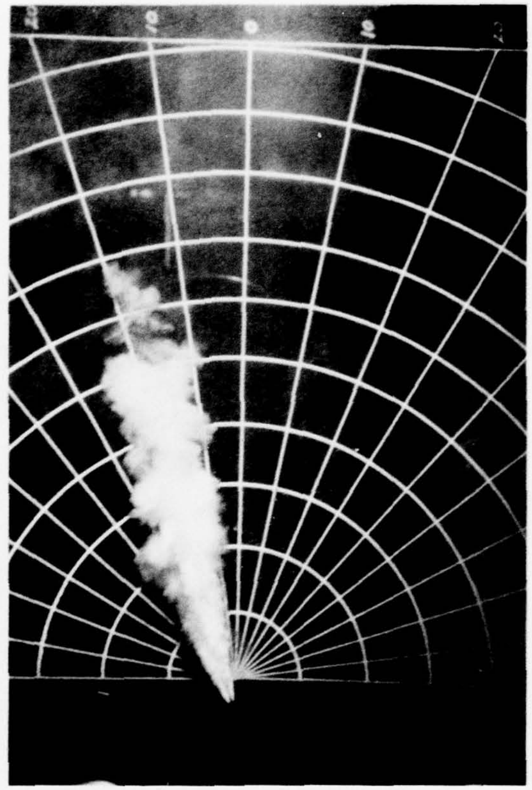
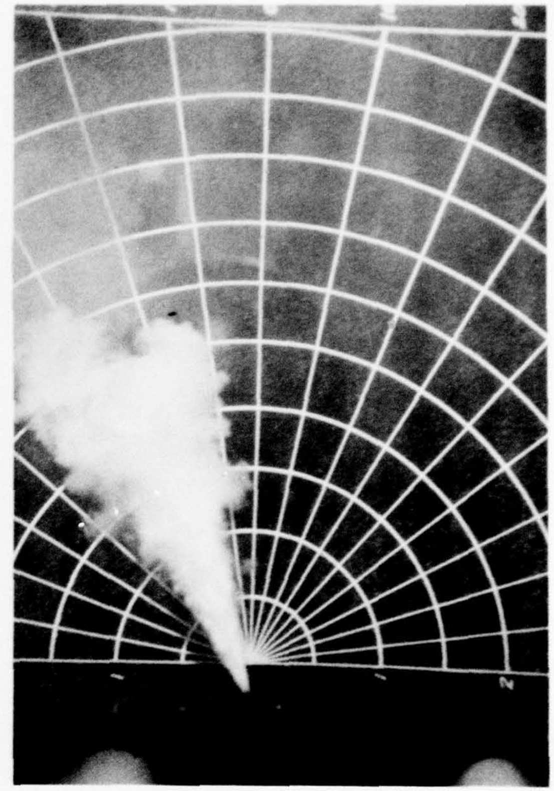
* Term which describes the sound produced when the injector needle repeated seats and lifts when subjected to continual high fuel pressure.



Good Injector From Cylinder 3
333 to 420 Hours



Injector Removed From Cylinder 2
at 337 Hours



Injector Removed From Cylinder 3
at 337 Hours

FIGURE 5. SPRAY PATTERN EVALUATIONS OF THE INJECTORS USING THE LIQUID INJECTOR TECHNIQUE

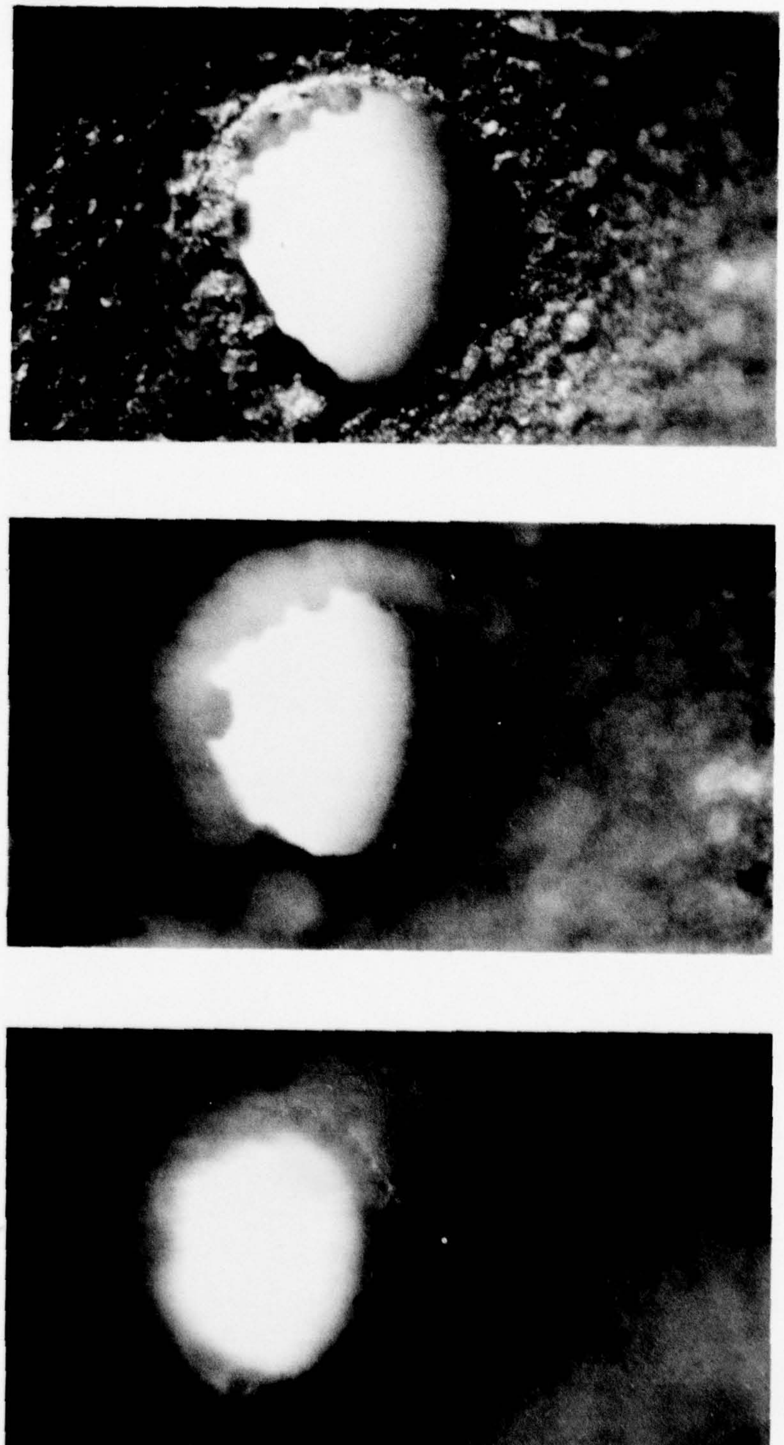


FIGURE 6. FUEL INJECTOR NOZZLE HOLE

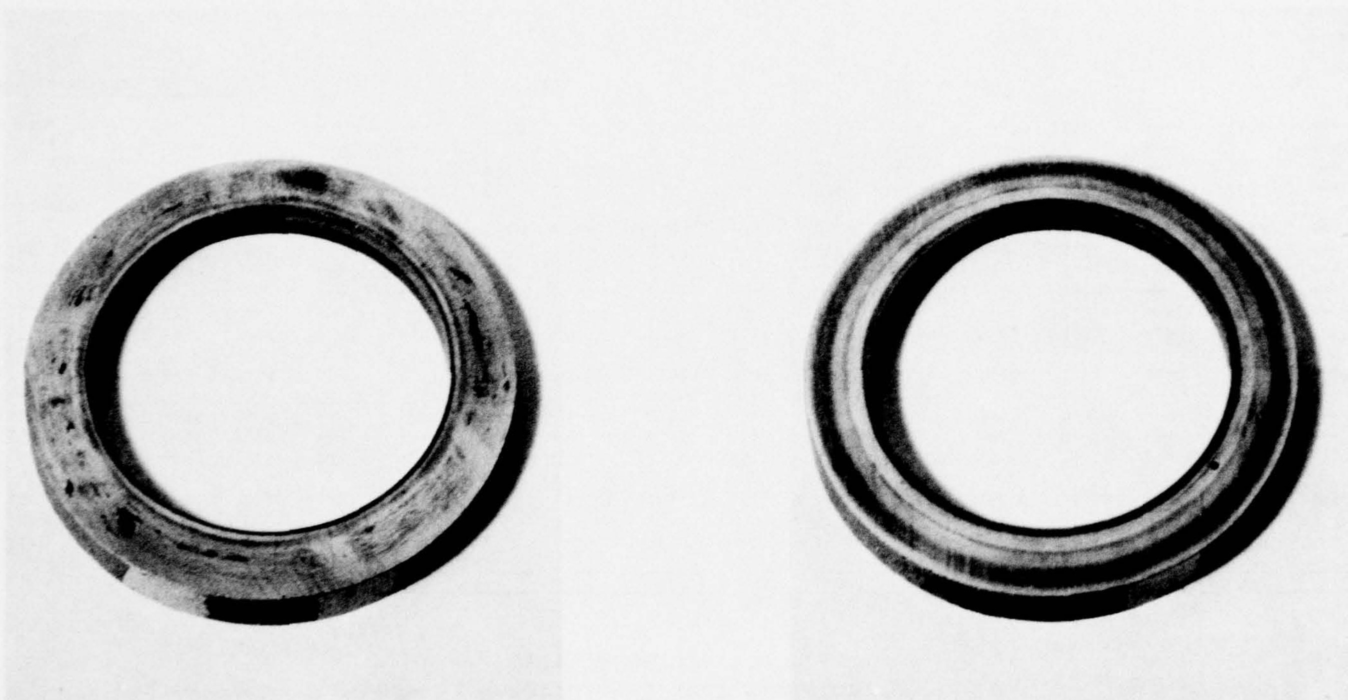


FIGURE 7.  FUEL INJECTION PUMP ADVANCE CONTROL RING

TABLE 4. LUBRICANT ANALYSIS
LDT-465 Water/Diesel Fuel Emulsion
Oil: REO-203

| | Method | New | 14 | 42 | 70 | 98 | 140 | 168 | 210 | 224 | 252 | 280 | 308 | 350 | 378 | 420 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | No. of Test Hours | | | | | | | | | | | | | |
| Gravity, °API | | | --- | --- | 26.2 | --- | 24.8 | --- | 23.4 | --- | --- | 25.1 | --- | 23.9 | --- | 22.5 |
| Kin. Vis. at 100°F, cSt | D 445 | 121.6 | 122.1 | 126.6 | 135.7 | 146.1 | 161.7 | 171.1 | 191.3 | 126.6 | 134.0 | 145.8 | 152.3 | 160.8 | 182.2 | 180.1 |
| Kin. Vis. at 210°F, cSt | D 445 | 12.6 | 12.7 | 12.9 | 13.6 | 14.5 | 15.4 | 15.9 | 17.2 | 12.79 | 13.42 | 14.16 | 14.70 | 15.27 | 16.37 | 16.66 |
| Total Acid No. | D 664 | 2.97 | --- | --- | 3.32 | --- | 4.16 | --- | 5.29 | --- | --- | 4.72 | --- | 5.76 | --- | 6.42 |
| Total Base No. | D 2896 | 5.08 | --- | --- | 5.96 | --- | 3.63 | --- | 5.98 | --- | --- | 5.31 | --- | 5.40 | --- | 5.22 |
| Petane Insols, % (w/coag) | D 893 | 0.03 | 0.31 | 0.71 | 1.14 | 1.67 | 2.36 | 2.81 | 3.85 | 0.66 | 1.10 | 1.67 | 2.18 | 3.00 | 3.48 | 4.65 |
| Benzene Insols, % (w/coag) | D 893 | 0.02 | 0.22 | 0.48 | 0.87 | 1.23 | 1.75 | 1.16 | 2.64 | 0.53 | 0.84 | 1.32 | 1.94 | 2.12 | 2.63 | 3.36 |
| Flash Point, °C | D 92 | | --- | --- | 232 | --- | 243 | --- | 238 | --- | --- | 240 | --- | 229 | --- | 232 |
| (°F) | | | --- | --- | (450) | --- | (470) | --- | (460) | --- | --- | (465) | --- | (445) | --- | (450) |
| Carbon Residue, % | D 524 | | --- | --- | 2.16 | --- | 2.95 | --- | 3.70 | --- | --- | 2.55 | --- | 3.15 | --- | 3.93 |
| Sulfated Ash, % | D 874 | | --- | --- | 1.30 | --- | 1.57 | --- | 1.78 | --- | --- | 1.41 | --- | 1.62 | --- | 1.84 |
| Water, % | | | --- | --- | 0.23 | --- | 0.42 | --- | 0.23 | --- | --- | 0.25 | --- | 0.17 | --- | 0.14 |
| Wear Metals, ppm | AA | | | | | | | | | | | | | | | |
| Fe | | | --- | --- | 87 | --- | 138 | --- | 174 | --- | --- | 64 | --- | 162 | --- | 163 |
| Cu | | | --- | --- | 7 | --- | 10 | --- | 12 | --- | --- | 6 | --- | 12 | --- | 13 |
| Cr | | | --- | --- | 1 | --- | 3 | --- | 8 | --- | --- | 2 | --- | 2 | --- | 2 |
| I.R. Trace No. | | | --- | --- | 1171 | --- | 1172 | --- | 1173 | --- | --- | 1175 | --- | 1176 | --- | 1177 |

--- = Not determined.

## IV. CONCLUSIONS

As a result of this investigation, the following conclusions were reached:

- The use of the 10 vol% water emulsion had no significant detrimental effects on engine cleanliness, wear, or oil degradation.
- No major mechanical changes were necessary in adapting the engine for use of this fuel.
- The engine could be started normally and would idle properly at all test temperatures encountered.
- Use of this fuel resulted in a 16-percent loss in power output during the 420-hour duration of the test.
- Fuel-injector problems encountered during the testing implicated fuel-origin deposits in the injection system as a possible reason for the power loss. This may be related to the high "existent gum" values of the fuel emulsion, which are attributed to the sugar-type surfactants used in this study.

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7. CRC Diesel Engine Rating Manual No. 1, Coordinating Research Council, Inc., New York, NY.

8. Proposed CRC Rating Systems for Diesel Engine Deposits, First Draft, Coordinating Research Council, Inc., New York, NY, February 1973.

9. Gray, J.T., Meckel, N.T., and Mannheimer, R.J., "Some Observations on the Liquid Injection Technique as a Research Tool," SAE Paper 660748.

# APPENDIX A

# TEST FUEL PROPERTIES

TABLE A-1. FUEL PROPERTIES

| Property | Ref. No. 2[a] DF (Cat-1G/1-H) | Low-Flash, Low-Sulfur DF: Neat | Low-Flash, Low-Sulfur DF: 10 vol% Water 2 vol% Surfactant |
|---|---|---|---|
| Gravity, °API @ 60°F | 33 | 33.9 | 29 |
| K. Vis at 38°C (100°F), cSt | 3.47 | 3.38 | 4.75 |
| Flash Point, °C | 58 | 63 | --[b] |
| Aniline Point, °C | 63 | 64 | 94 |
| Cetane No. | 47[c] | 50.5 | 42.8 |
| Pour Point, °C | -2 | --- | -2 |
| Water and Sediment | 0.0 | --- | --- |
| Carbon Residue, % | 0.2 | --- | 0.4 |
| Sulfur, % | 0.415 | 0.056 | --- |
| Acid No. | 0.04 | 0.006 | 0.16 |
| Copper Corrosion | 1A | --- | 1A |
| Distillation, °C | | | |
| IBP | 210 | 151 | --- |
| 10% | 242 | 242 | --- |
| 50% | 270 | 284 | --- |
| 90% | 317 | 340 | --- |
| FPB | 365 | 370 | --- |
| Higher Heating Value, kJ/kg(Btu/lb) | 45,470(19,550)[d] | 45,100(19,390) | --- |
| Accelerated Stability, Total Insols., mg/100ml | 0.8 | --- | 2.1 |
| Ash, % | 0.001 | <0.001 | <0.003 |
| Existent Gum, mg/100ml | 7 | 4.5 | 1418 |

a. Federal Test Standard 791B, Method 341.4, Section 4.1.
b. Ambiguous Intermittent Flame.
c. Calculated cetane value.
d. Calculated from gravity, viscosity, and distillation properties.

TABLE A-2. SUMMARY OF FLAMMABILITY AND BALLISTIC VULNERABILITY CHARACTERISTICS OF FIRE-RESISTANT DIESEL FUEL

| Flammability Property | Neat Diesel Fuel | 10% Water and 2% Surfactant In Diesel Fuel |
|---|---|---|
| Flash Point, °C | 58 | --* |
| Fire Point, °C | 88 | 110 |
| Autoignition Temperature | 243 | 413–427 |
| Horizontal Flame Propagation, Minutes After Pilot Wick Ignition Before Flame Propagation | 0.6 | No Propagation |
| AFLRL Mist Flashback Rating, cm | 19.6 | 10.5 |
| AFLRL 20-mm HEIT Ballistic Test | | |
| Fireball: | Filled Target Enclosure | Smaller than with Neat Fuel |
| Residual Fire: | Entire Fuel Spill Ignited | Fraction of Fuel Spill Ignited |
| Residual Fire Extinguishment: | Manual Extinguishment Difficult Because of Intense Heat | Self-Extinguished in 15 Seconds |

* Ambiguous Intermittent Flame

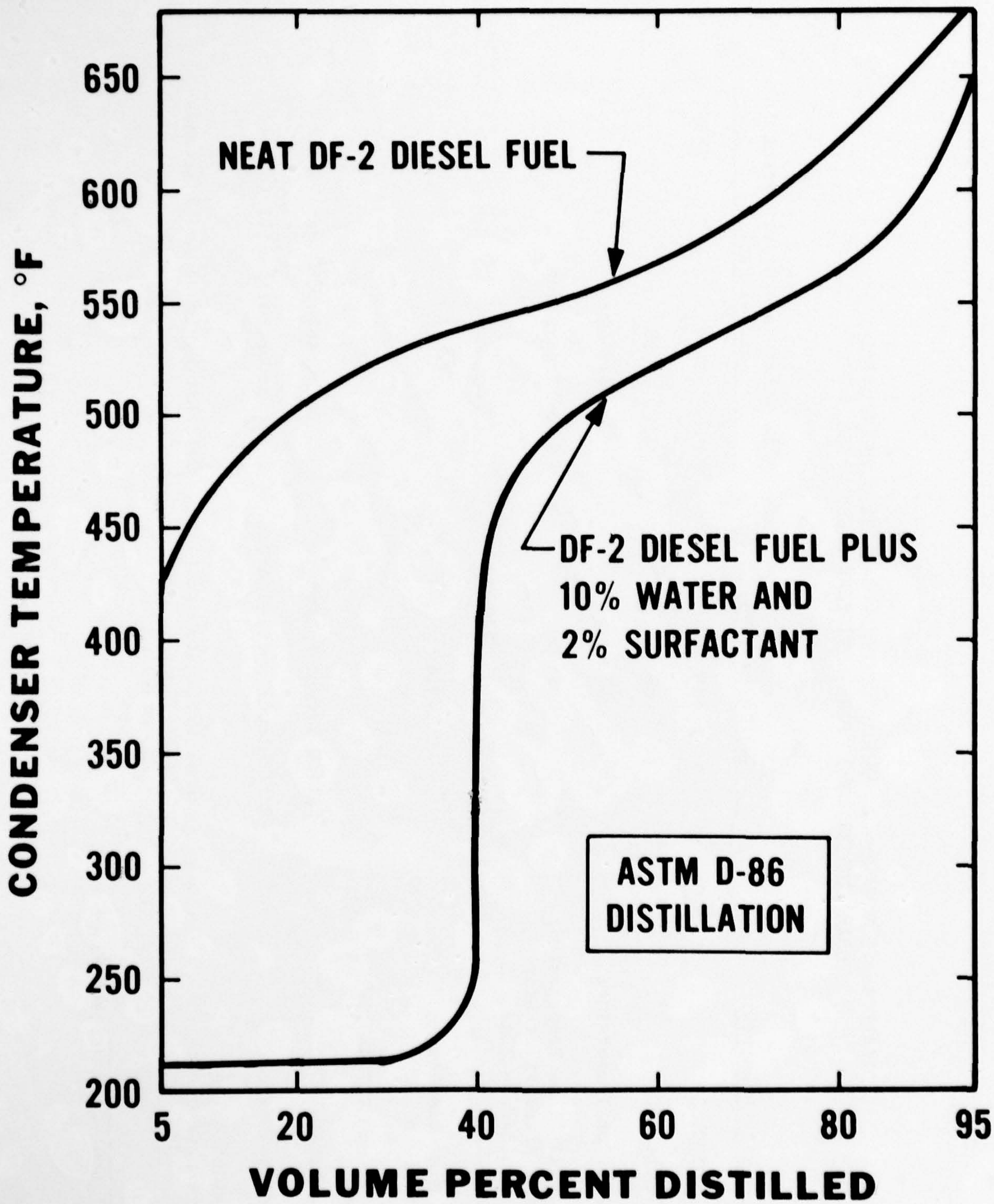


FIGURE A-1. DISTILLATION CHARACTERISTICS OF 10% WATER-IN-DIESEL FUEL MACROEMULSION

APPENDIX B

COMPATIBILITY TEST PROCEDURE
WHEELED-VEHICLE TEST CYCLE
LDT-465-1C ENGINE

## ARMY/CRC WHEELED VEHICLE ENDURANCE TEST CYCLE

The 210-hour test cycle is conducted in accordance with the following operating procedure.

1. The engine will be broken in on test oil using a cycle based on the engine manufacturer's recommendations. Oil will then be drained, and the engine filled with fresh oil.

2. Power check the engine. By this is meant the determination of the full-load performance characteristics of the engine across the speed range. This includes such items as power, torque, fuel flow, and all pertinent temperatures and pressures.

3. Conduct the 210-hour endurance phase in accordance with the following schedule:

| Duration (Hr) | Load (%) | Speed | Water Temp (°F) |
|---|---|---|---|
| 2 | 100 | Rated ± 20 rpm | 180 ± 5°F |
| 1 | 0 | Idle | 100* ± 5°F |
| 2 | 100 | Rated | 180 |
| 1 | 0 | Idle | 100* |
| 2 | 100 | Rated | 180 |
| 1 | 0 | Idle | 100* |
| 2 | 100 | Rated | 180 |
| 1 | 0 | Idle | 100* |
| 2 | 100 | Rated | 180 |
| 10 | Shutdown | | |

* This temperature will be attained within 10 minutes of start of idle.

4. The following test data will be determined and recorded at hourly intervals as a minimum:

   Engine speed
   Engine load
   Fuel consumption
   Blowby
   Intake pressures (before and after compressor where applicable)
   Exhaust pressures (before and after turbine where applicable)
   Fuel pressure
   Oil pressure
   Temperatures:
   - Water (to and from engine)
   - Oil (gallery and sump)
   - Fuel to engine
   - Intake (before and after compressor where applicable)
   - Exhaust (each cylinder)
   - Wet and dry bulb ambients
   - Exhaust (before and after turbine where applicable)

   Barometric pressure

5. Oil temperature will be controlled by coolant temperature. It will not be allowed to exceed 240°F.

6. Power check the engine.

7. At the completion of the test, the engine will be torn down, inspected, and gaged. Inspection will be in accordance with CRC procedures.

# APPENDIX C

## 420-HOUR TEST RESULTS

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TABLE C-1. LDT-465
420-HOUR ENDURANCE TEST
BUILD-UP ENGINE MEASUREMENTS

| | Inches | | | |
|---|---|---|---|---|
| | Min | Max | Avg | Specified Limits |
| Cylinder Liners (Installed) | | | | |
| Inside Diameter | 4.5597 | 4.5612 | 4.5606 | |
| Out-Of-Round | 0.0002 | 0.0008 | 0.0005 | 0.0015 max |
| No. 1 Ring | | | | |
| End Gap | 0.019 | 0.022 | 0.021 | |
| No. 2 Ring | | | | |
| End Gap | 0.019 | 0.022 | 0.020 | |
| No. 3 Ring | | | | |
| End Gap | 0.019 | 0.023 | 0.020 | 0.016-0.028 |
| Side Clearance | 0.003 | 0.004 | 0.003 | 0.0025-0.0045 |
| No. 4 Ring | | | | |
| End Gap | 0.017 | 0.020 | 0.019 | 0.016-0.028 |
| Side Clearance | 0.001 | 0.001 | 0.001 | 0.0005-0.0025 |

TABLE C-2. SUMMARY OF OPERATING CONDITIONS FOR DOUBLE (420-HR) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-emulsified DF-2 Lubricant: REO 203, Grade 30

| | Minimum | Maximum | Average |
|---|---|---|---|
| Speed, rpm | 2600 | 2620 | 2605 |
| BMEP, kPa (psi) | 445.5(64.6) | 619.8(89.9) | 525.8(76.3) |
| Obs. Power, kW (BHp) | 76.4(102.5) | 106.3(142.6) | 90.4(121.2) |
| Fuel Rate, kg/hr (lb/hr) | 26.18(57.60) | 32.68(71.90) | 31.16(68.55) |
| BSFC, kg/kW-hr (lb/BHp-hr) | 0.292(0.479) | 0.403(0.661) | 0.346(0.567) |
| Blowby, scm/hr (scf/hr) | 0.0(0.0) | 7.8(273.9) | 5.7(200.8) |
| Temperatures, °C(°F) | | | |
| Jacket Coolant-in | 73(164) | 81(177) | 77(171) |
| Jacket Coolant-out | 78(172) | 87(188) | 83(181) |
| Sump Oil | 97(206) | 121(250) | 111(231) |
| Ambient Air | 19(67) | 34(93) | 27(81) |
| Intake Manifold | 84(183) | 119(247) | 103(218) |
| Exhaust (after turbo) | 371(700) | 660(1220) | 541(1007) |
| Compressor, $\Delta T$ | 38(101) | 72(162) | 58(137) |
| Turbine, $\Delta T$ | 2(3.6) | 146(295) | 52(125) |
| Pressures | | | |
| Intake Manifold, kPa (in. Hg) | 24.3(7.2) | 37.5(11.1) | 32.0(9.0) |
| Exhaust, Absolute, kPa (in. Hg) | 30.0(8.9) | 41.2(12.2) | 36.0(10.7) |
| Turbine, $\Delta P$, kPa (in. Hg) | 21.6(6.4) | 33.8(10.0) | 29.8(8.8) |
| Gallery Oil, kPa (in. Hg) | 331(48) | 455(66) | 361(52) |

TABLE C-3. SUMMARY OF DEPOSIT RATINGS FOR DOUBLE (420-hr) WHEELED-VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-emulsified DF-2 Lubricant: REO 203, Grade 30

| | Piston No. 1 | 2 | 3 | 4 | 5 | 6 | Avg |
|---|---|---|---|---|---|---|---|
| **Pistons** | | | | | | | |
| WDT[1] Rating | 312 | 287 | 292 | 313 | 323 | 379 | 318 |
| No. 1 Groove Carbon Fill, vol% | 78 | 70 | 67 | 72 | 81 | 86 | 75 |
| No. 1 Groove RSC, % | 15.0 | 17.0 | 16.3 | 16.3 | 18.8 | 18.8 | 17.0 |
| No. 2 Groove RSC, % | 20.0 | 15.0 | 17.5 | 13.8 | 20.0 | 22.5 | 18.1 |
| Skirt Lacquer, % | | | | | | | |
| Light Amber | 10 | 12 | 10 | 5 | 10 | 20 | 11 |
| Very Light Amber | 15 | 23 | 15 | 35 | 20 | 40 | 26 |
| Carbon and Ash Demerits | | | | | | | |
| Piston Top | 1.0 | 0.9 | 0.9 | 0.9 | 1.0 | 0.9 | 0.9 |
| Combustion Chamber | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| **Piston Rings (ID only)** | | | | | | | |
| Top Ring, Lacquer Demerits | 0.4 | 0 | | 0 | 0 | 0 | |
| Carbon, %[2] | 85-H | 90-H, 10-L | 100-H | 100-H | 100-H | 100-H | |
| No. 2 Ring, Lacquer Demerits | 0 | 0.5 | 0 | 0 | 1.3 | 0 | |
| Carbon, %[2] | 100-H | 90-H | 100-H | 100-H | 30-H, 10-L | 100-H | |
| No. 3 Ring, Lacquer Demerits | 0.4 | 0 | 0 | 0 | 0 | 0 | |
| Carbon, %[2] | 95-H | 100-H | 100-H | 100-H | 100-H | 100-H | |
| Oil Ring, Lacquer Demerits | 7.0 | 8.0 | 8.0 | 8.0 | 7.0 | 8.0 | |
| Carbon Demerits | 0 | 0 | 0 | 0 | 0 | 0 | |
| **Cylinder No. (Percent of Total Ring Travel Area) — Cylinders** | | | | | | | |
| Lacquer, % | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Glazing, % | 40 | 30 | 15 | 20 | 18 | 20 | 24 |
| **Cylinder Head** | | | | | | | |
| Carbon and Ash, Area % | | | | | | | |
| Heavy | 0 | 0 | 0 | 0 | 0 | 0 | |
| Medium | 3 | 2 | 3 | 3 | 4 | 2 | |
| Light | 97 | 98 | 97 | 97 | 95 | 98 | |

| | | Valves 1 | | 2 | | 3 | |
|---|---|---|---|---|---|---|---|
| Area | | Carb | Lacq | Carb | Lacq | Carb | Lacq |
| Head | INT[3] | 100A(s) | --- | 100A(s) | --- | 100A(s) | --- |
| | EXH | --- | 100LA[4] | --- | 100LA | 100soot | --- |
| Face | INT | --- | MOD.BL.[4] | --- | MOD.BL. | --- | MOD.BL. |
| | EXH | --- | 100LA | --- | 100LA | --- | 100LA |
| Tulip[5] | INT | 1.5 | --- | 1.5 | --- | 1.5 | --- |
| (Demerits) | EXH | 1.5 | --- | 1.5 | --- | 1.5 | --- |
| Stem | INT[6] | Clean | ------------ | ------------ | ------------ | ------------ | ------------ |
| | EXH[7] | Clean | ------------ | ------------ | Hvy BR/BL[4] | ------------ | ------------ |

| | | Valve 4 | | 5 | | 6 | |
|---|---|---|---|---|---|---|---|
| Area | | Carb | Lacq | Carb | Lacq | Carb | Lacq |
| Head | INT | 100soot | --- | 100A(s) | --- | 100soot | --- |
| | EXH | 100soot | --- | 100soot | --- | 100soot | --- |
| Face | INT | --- | MOD.BL. | --- | MOD.BL. | --- | MOD.BL. |
| | EXH | 100soot | --- | 100soot | --- | --- | 100LA |
| Tulip | INT | 1.5 | --- | 1.5 | --- | 1.5 | --- |
| (Demerits) | EXH | 1.5 | --- | 1.5 | --- | 1.5 | --- |
| Stem | INT | ------------ | ------------ | ------------ | ------------ | ------------ | ------------ |
| | EXH | ------------ | ------------ | ------------ | Hvy BR/BL | ------------ | ------------ |

(1) Weighted Total Deposits
(2) H-Heavy, L-Light
(3) (s) - soft carbon deposit.
(4) LA - light amber lacquer; BL - black lacquer; BR - brown lacquer.
(5) All tulips indicate an ash-like deposit, which intakes have sooted over.
(6) Valve guide leakage indicated on all intake stems.
(7) No. 4 exhaust stem tight in guide.

TABLE C-4. SUMMARY OF WEAR DATA FOR DOUBLE (420-HR) WHEELED-VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-emulsified DF-2 Lubricant: REO 203, Grade 30

Cylinder Bore Increase, mm x $10^{-4}$ (in. x $10^{-4}$)

| | Cylinder No. | | | | | | |
|---|---|---|---|---|---|---|---|
| Longitudinal Axis | 1 | 2 | 3 | 4 | 5 | 6 | Avg |
| Top Ring at TDC | 483(19) | 863(34) | 635(25) | 711(28) | 838(33) | 762(30) | 715(28) |
| 90 deg | 101(4) | 584(23) | 559(22) | 635(25) | 533(21) | 635(25) | 508(20) |
| BDC | 51(2) | 584(23) | 508(20) | 635(25) | 686(27) | 610(24) | 512(20) |
| Transverse Axis | | | | | | | |
| Top Ring at TDC | 1168(46) | 762(30) | 813(32) | 889(35) | 813(32) | 940(37) | 898(35) |
| 90 deg | 1194(47) | 711(28) | 864(34) | 838(33) | 965(38) | 813(32) | 898(35) |
| BDC | 1092(43) | 737(29) | 636(29) | 813(32) | 660(26) | 762(30) | 783(32) |

Piston Ring End Gap Increase (In gauge block), mm x $10^{-3}$ (in. x $10^{-3}$)

| | Piston No. | | | | | | |
|---|---|---|---|---|---|---|---|
| Ring | 1 | 2 | 3 | 4 | 5 | 6 | Avg |
| Top | 25(1) | -25(-1) | 25(1) | 0(0) | 0(0) | -25(-1) | 0(0) |
| No. 2 | 76(3) | 51(2) | 0(0) | 25(1) | 25(1) | 25(1) | 34(1.3) |
| No. 3 | 51(2) | 25(1) | 25(1) | 0(0) | -51(-2) | 0(0) | 8(0.3) |
| No. 4 (oil) | 25(1) | 51(2) | 25(1) | 25(1) | 0(0) | 25(1) | 25(1.0) |

Piston Ring Side Clearance Increase, mm x $10^{-3}$ (in. x $10^{-3}$)

| Ring | 1 | 2 | 3 | 4 | 5 | 6 | Avg |
|---|---|---|---|---|---|---|---|
| No. 3 | 0(0) | 0(0) | 0(0) | -13(-0.5) | -13(-0.5) | 0(0) | -4(-0.2) |
| No. 4 (oil) | 0(0) | 13(0.5) | 13(0.5) | 0(0) | 13(0.5) | 0(0) | 7(0.3) |

TABLE C-5. SUMMARY OF SURFACE CONDITIONS FOR DOUBLE (420-HR) WHEELED CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-emulsified DF-2 Lubricant: REO 203, Grade 30

| | Piston No. 1 | 2 | 3 | 4 | 5 | 6 | Avg |
|---|---|---|---|---|---|---|---|
| | | | Pistons | | | | |
| Top Land | All Normal | | | | | | |
| Skirt | Lt. Vertical Lines on All | | | | | | |
| Piston Pin | All Normal | | | | | | |
| | | | Piston Rings | | | | |
| Ring Face[(1)] | | | | | | | |
| Top Ring, % burned | 10 | 30 | 0 | 40 | 20 | 40 | 23 |
| Scuffing | light | N | N | N | N | N | |
| Scoring | Y | N | N | N | N | N | |
| No. 2 Ring, % burned | 1 | 0 | 30 | 0 | 3 | 30 | 11 |
| Scuffing | light | N | N | N | N | N | |
| Scoring | Y | N | N | N | N | N | |
| No. 3 Ring, % burned | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Scuffing | light | N | N | N | N | N | |
| Scoring | Y | N | N | N | N | N | |
| Oil Ring | | | | | | | |
| Scuffing | N | light | N | N | N | N | |
| Scoring | Y | N | N | N | N | N | |

| | Cylinder No. 1 | 2 | 3 | 4 | 5 | 6 | Avg |
|---|---|---|---|---|---|---|---|
| | | | Cylinders | | | | |
| Percent of Total Ring Travel Area Scuffed | 4 | 0 | 2 | 2 | 2 | 3 | 2 |
| | | | Valves | | | | |
| Intakes | | | | | | | |
| Freedom in Guide | F | F | F | F | F | F | |
| Head | N | N | N | N | N | N | |
| Face | N | N | N | N | N | N | |
| Seat | (2) | (2) | (2) | N | N | N | |
| Stem | N | N | N | N | N | N | |
| Tip | N | N | N | N | N | N | |
| Exhausts | | | | | | | |
| Freedom in Guide | F | F | F | (3) | F | F | |
| Head | N | N | N | N | N | N | |
| Face | N | N | N | N | N | N | |
| Seat | N | N | N | N | N | N | |
| Stem | N | N | N | N | N | N | |
| Tip | N | N | N | N | N | N | |

| | Other Surfaces: Connecting Rod No. 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Rod Bearing | 10%(4) (5,6) | --- (5,6) | 10%(4) (5,6) | --- (5,6) | --- (5,7) | 2%(4) (5,6) |
| Piston Pin | N | N | N | N | N | N |

(1) Moderate amount of vertical scratches on all rings.
(2) Light pitting.
(3) Tight but not seized.
(4) Light wiping.
(5) Longitudinal chatter indicated.
(6) Trace debris embedment.
(7) One medium dirt scratch.

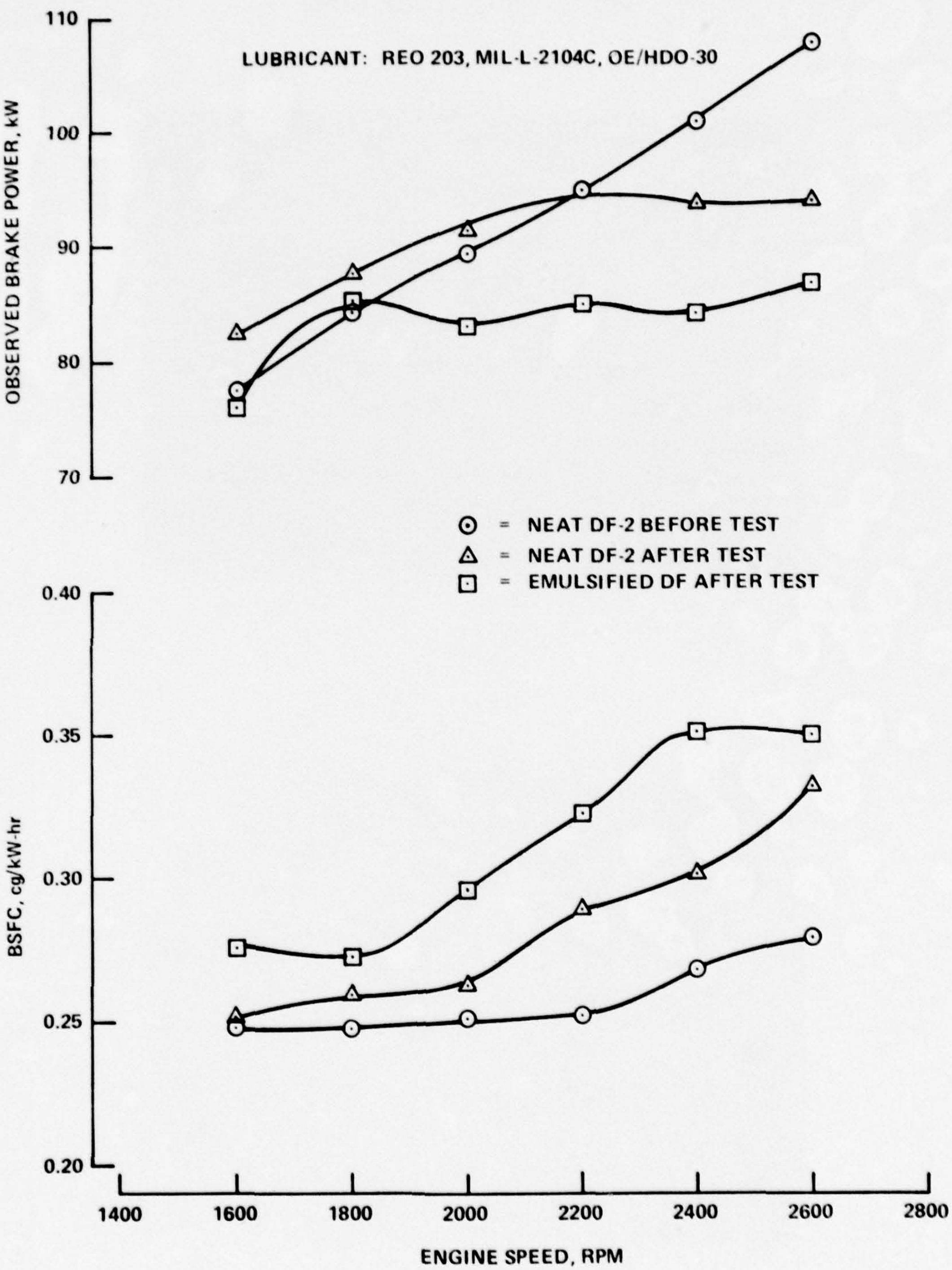
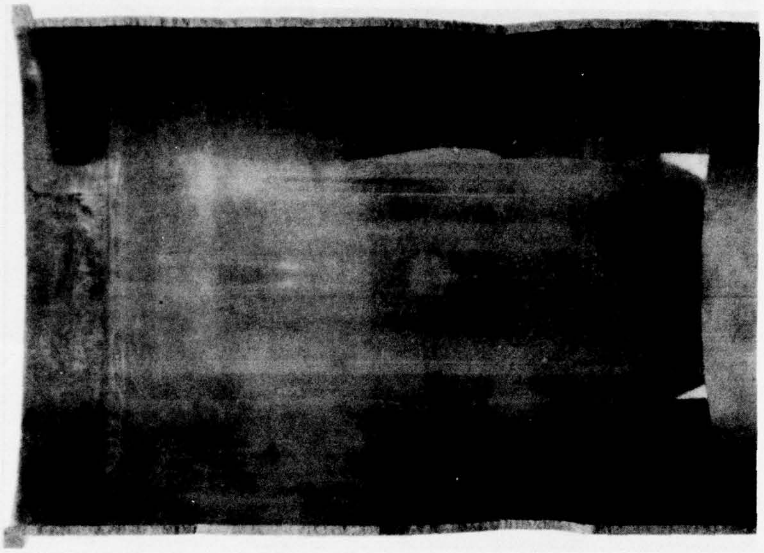


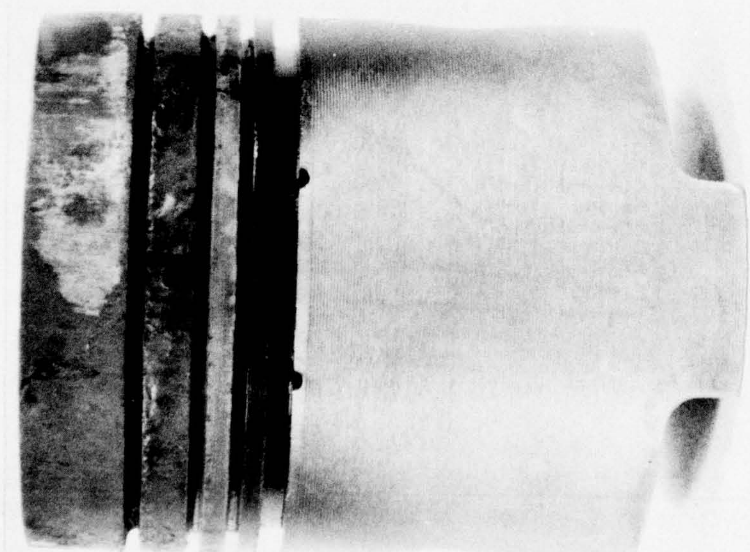

FIGURE C-1. FULL-RACK PERFORMANCE CALIBRATION OF LDT-465-1C ENGINE

DOUBLE (420-Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203,Grade 30

PISTON AND CYLINDER LINER



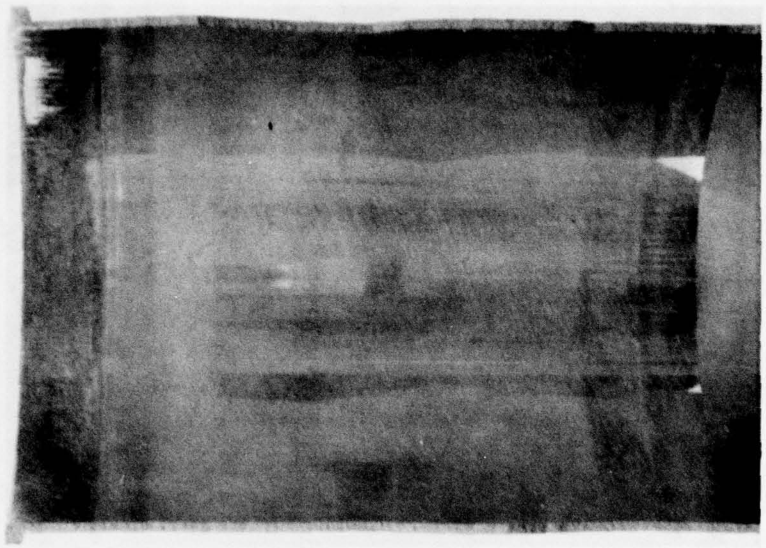


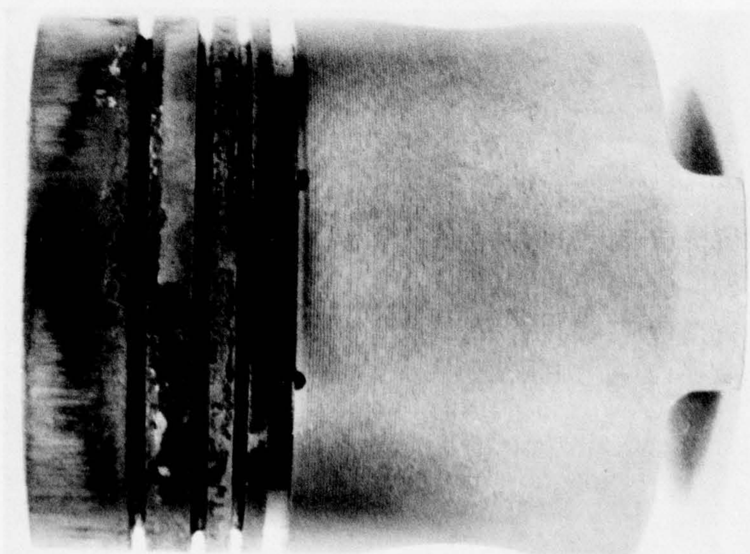
Cylinder 1
Thrust

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C  Fuel: 10% Water-Emulsified DF  Lubricant: REO-203,Grade 30

PISTON AND CYLINDER LINER



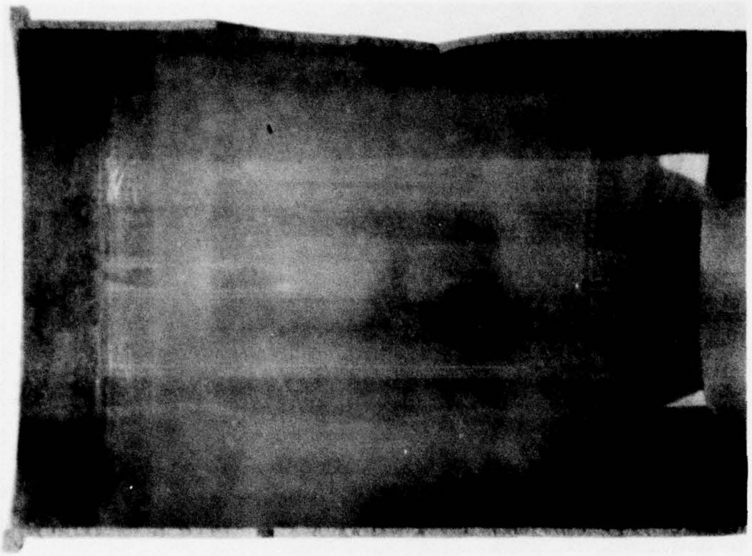


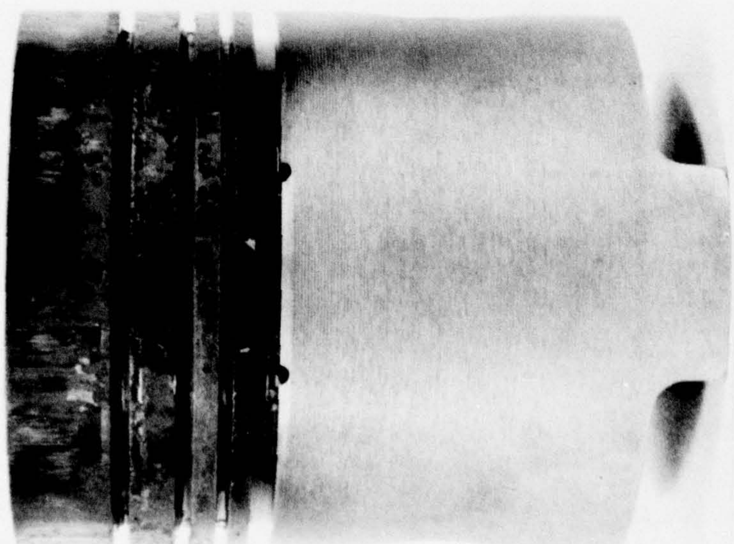
Cylinder 1
Anti-Thrust

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

PISTON AND CYLINDER LINER



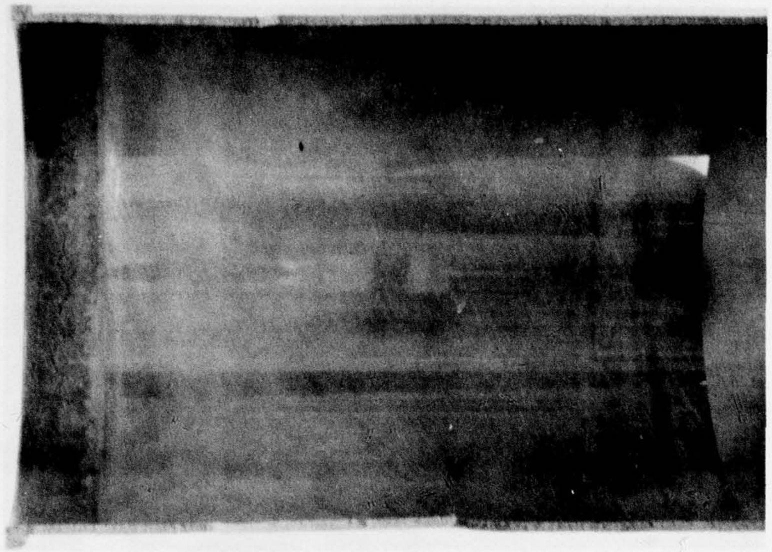


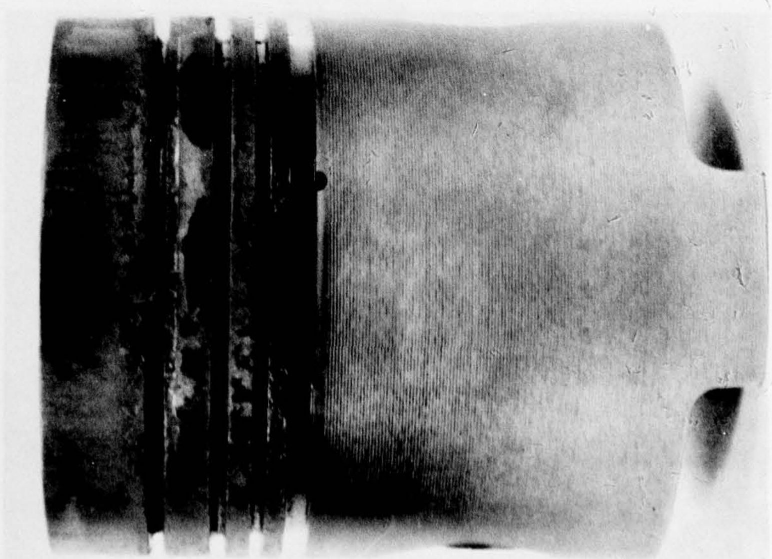
Cylinder 2
Thrust

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

PISTON AND CYLINDER LINER



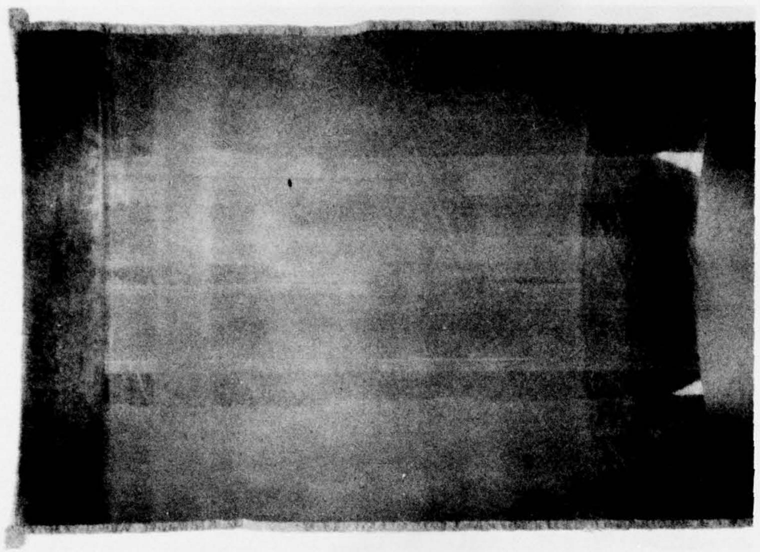


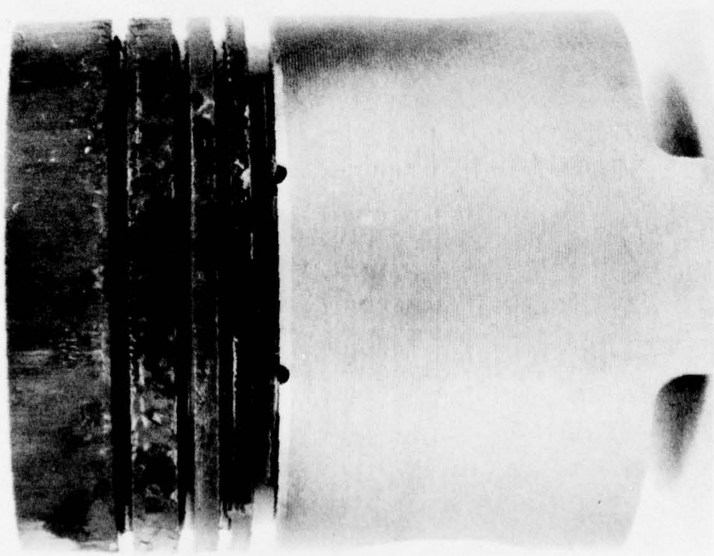
Cylinder 2
Anti-Thrust

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

PISTON AND CYLINDER LINER



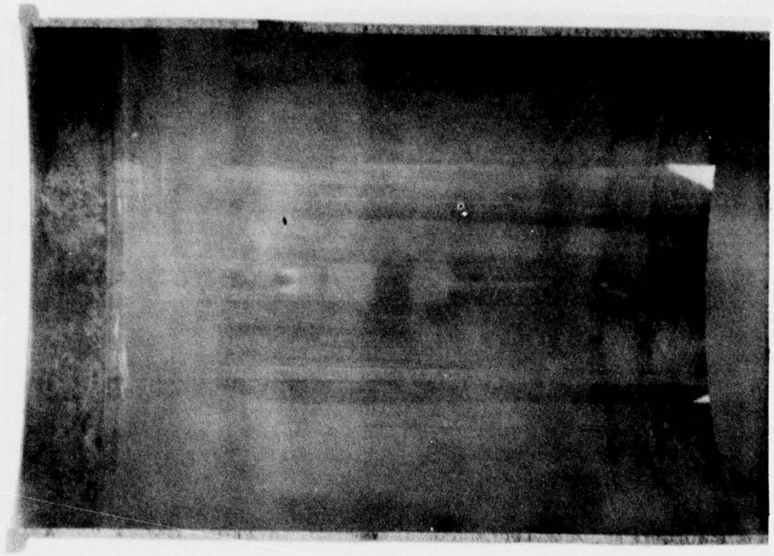


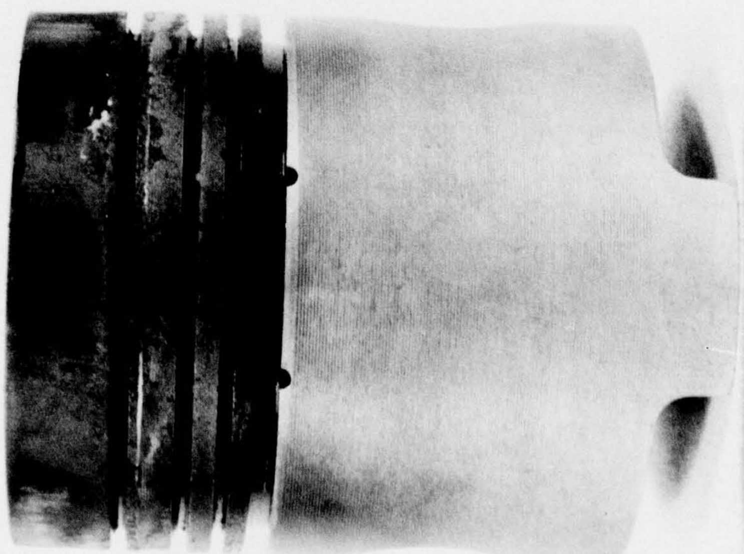
Cylinder 3
Thrust

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

PISTON AND CYLINDER LINER



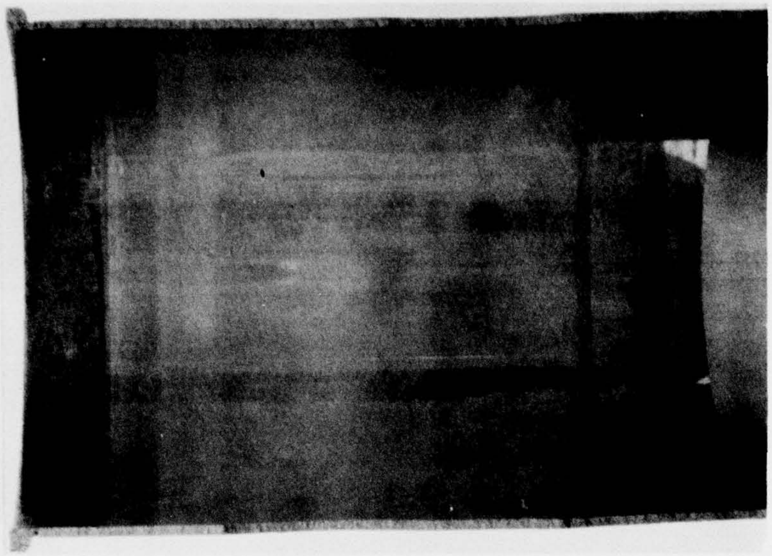


Cylinder 3
Anti-Thrust

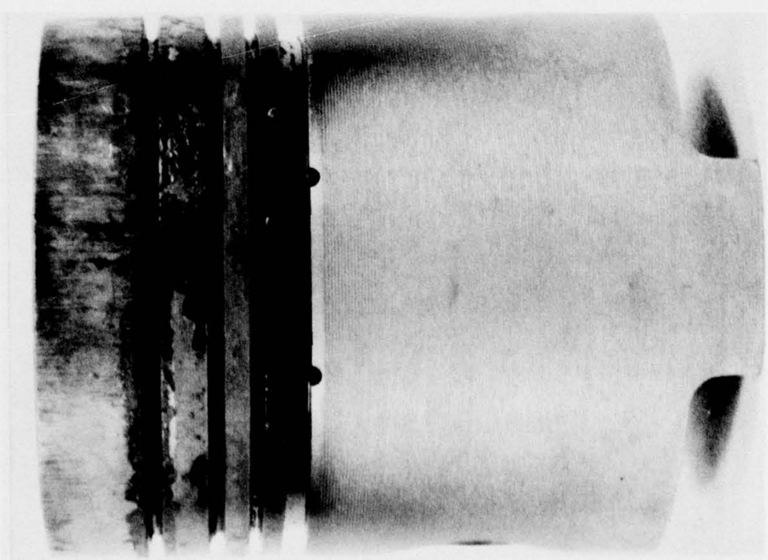
DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

PISTON AND CYLINDER LINER



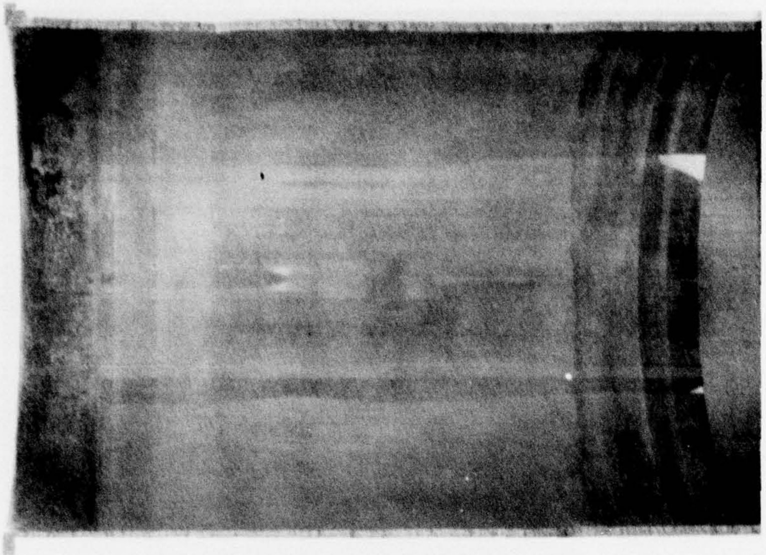
Cylinder 4
Thrust

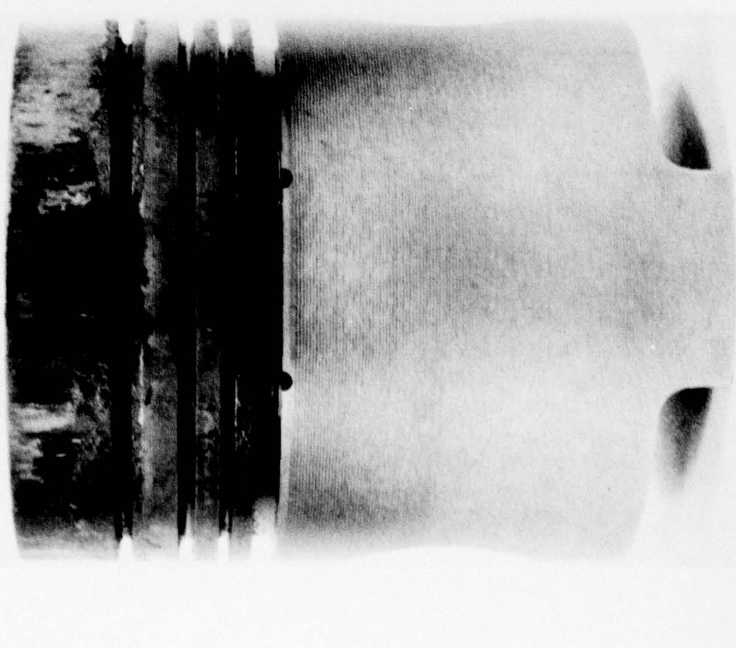


DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

PISTON AND CYLINDER LINER



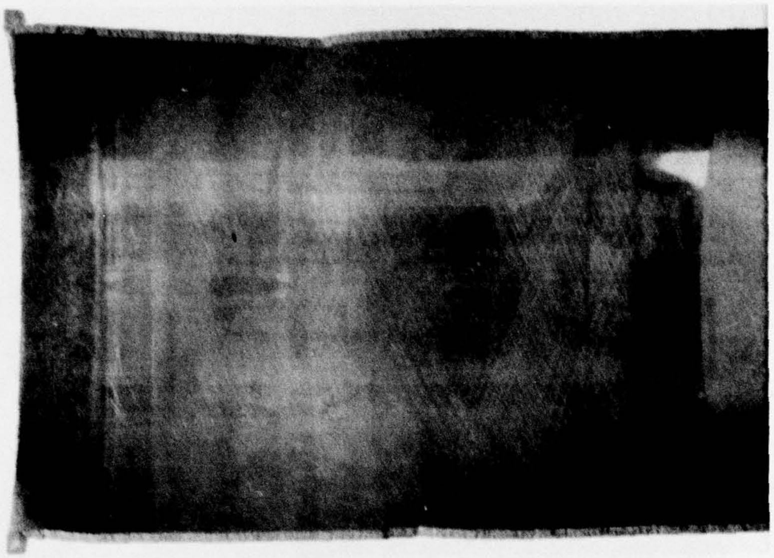


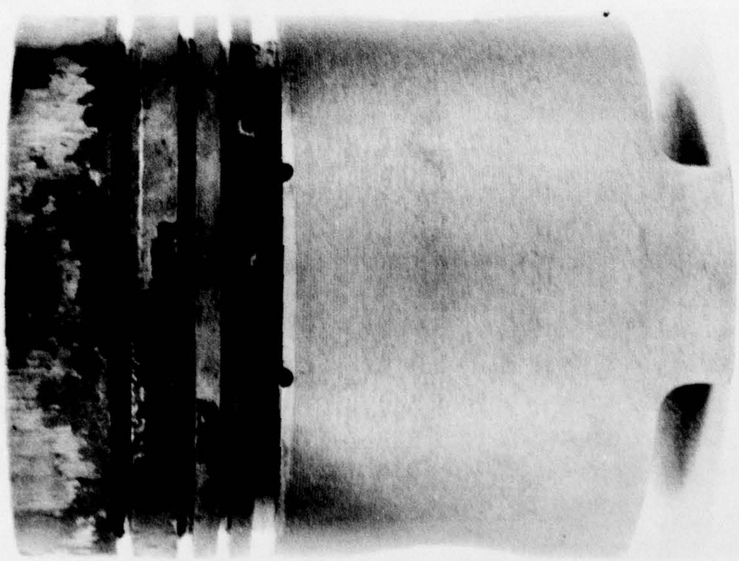
Cylinder 4
Anti-Thrust

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

PISTON AND CYLINDER LINER



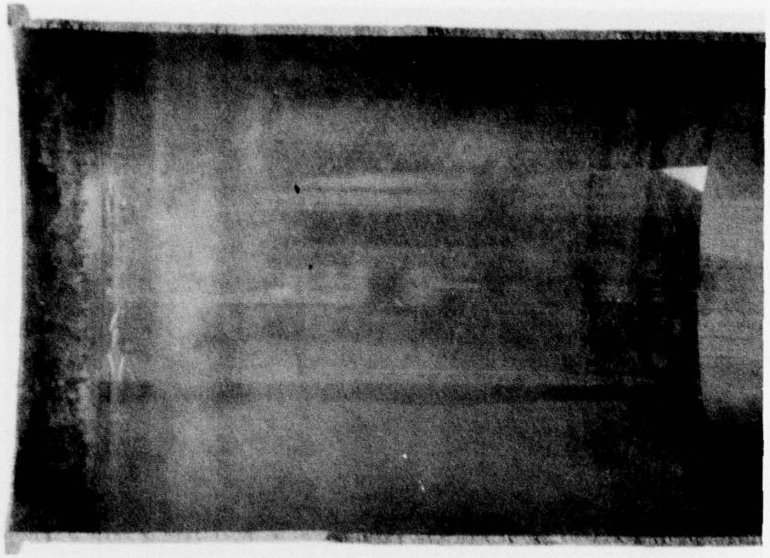


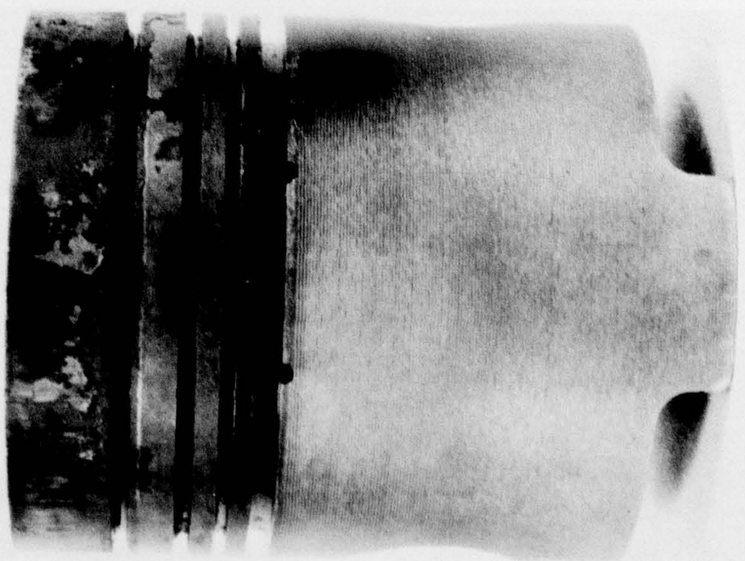
Cylinder 5
Thrust

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

PISTON AND CYLINDER LINER



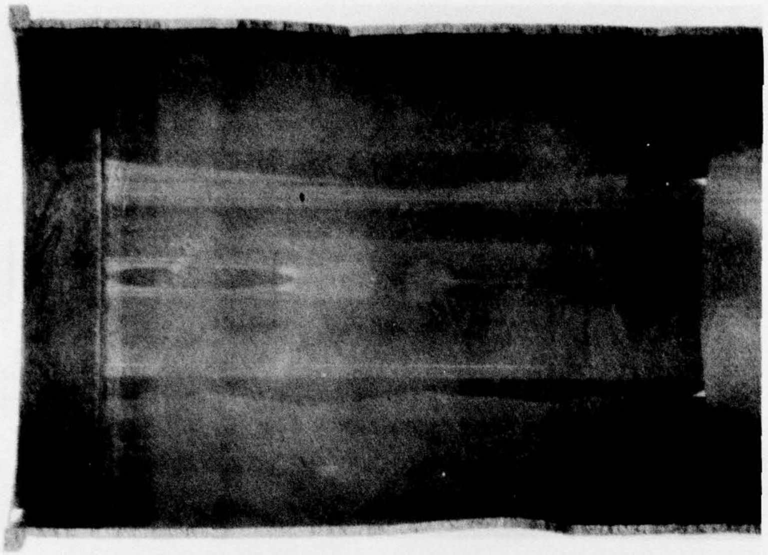


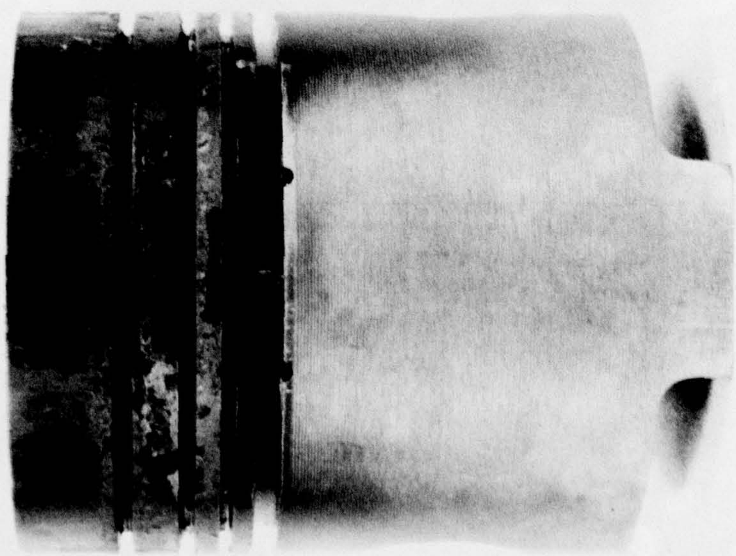
Cylinder 5
Anti-Thrust

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

PISTON AND CYLINDER LINER



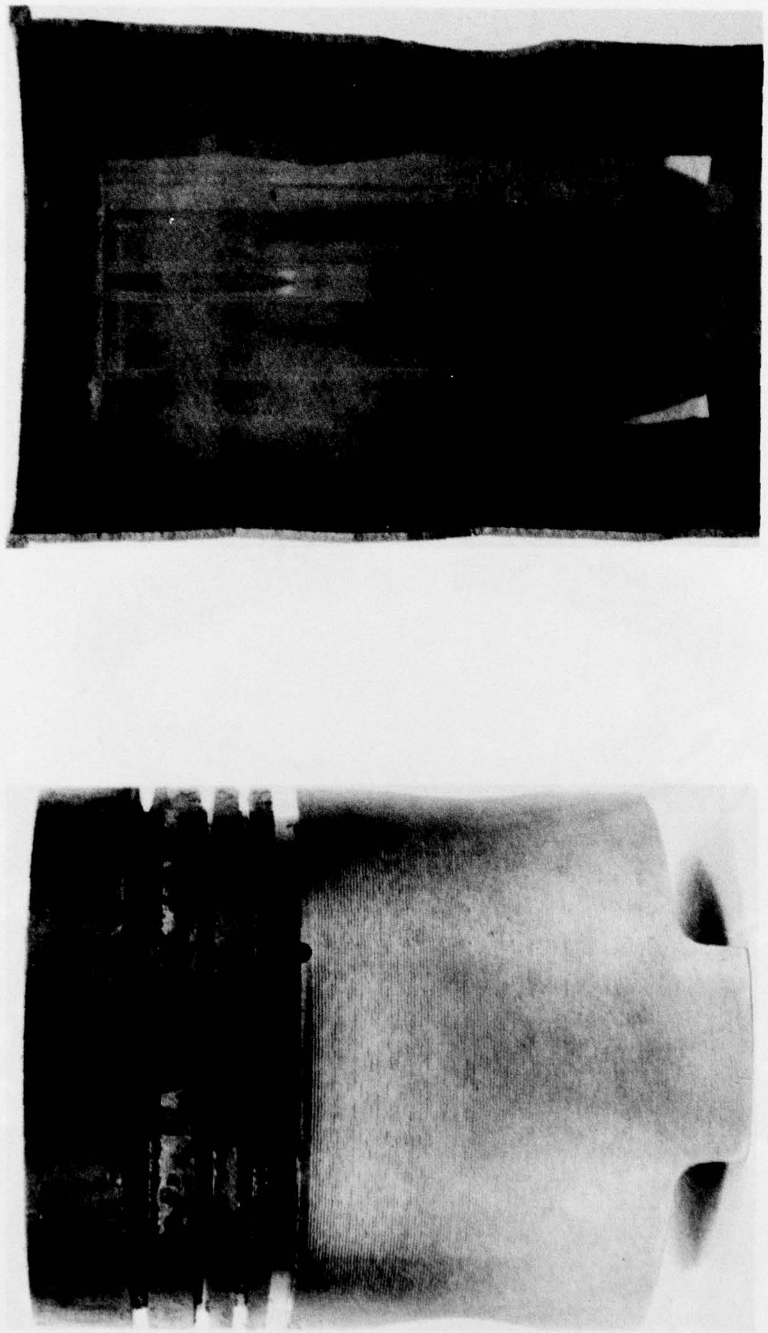


Cylinder 6
Thrust

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

PISTON AND CYLINDER LINER

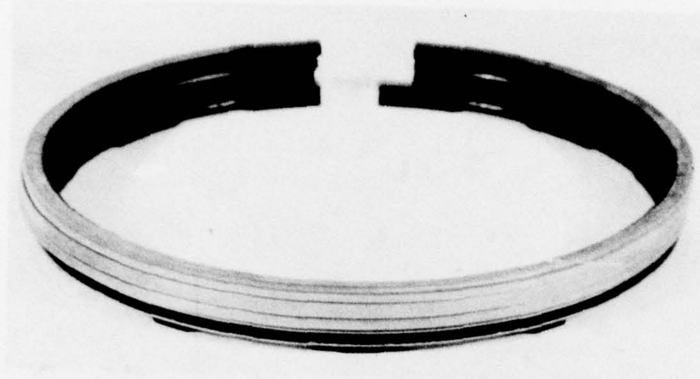


Cylinder 6
Anti-Thrust

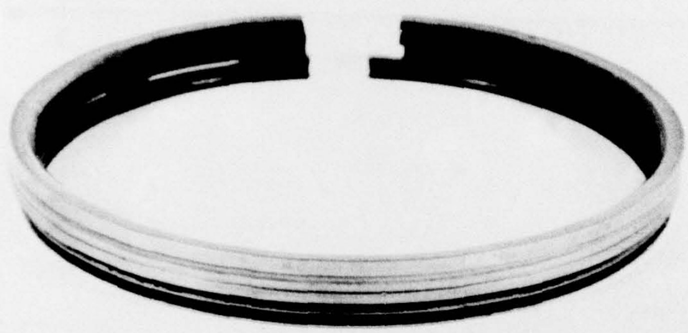
DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

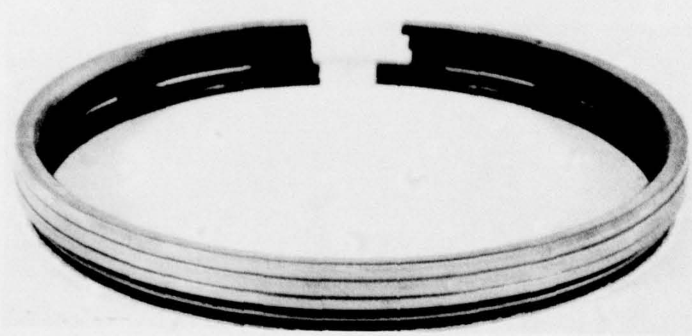
PISTON RING SETS



Cylinder 1



Cylinder 2

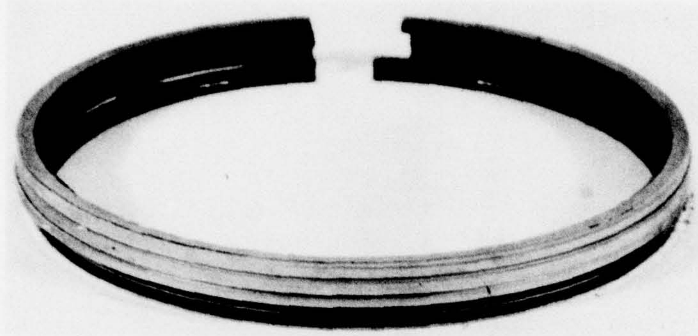


Cylinder 3

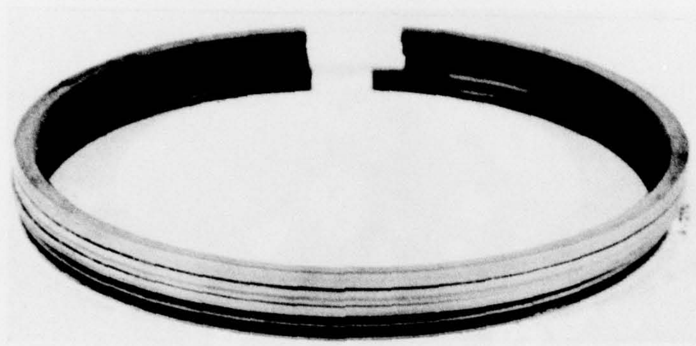
DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

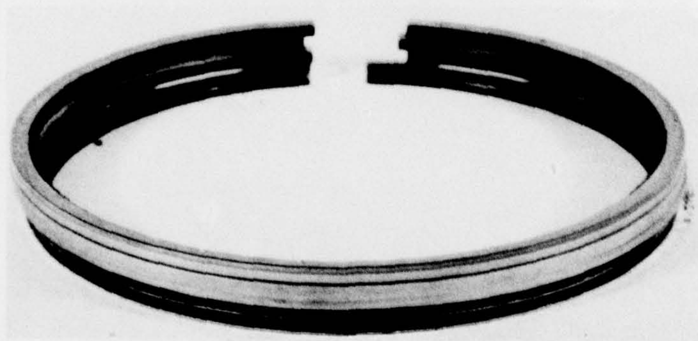
PISTON RING SETS



Cylinder 4



Cylinder 5

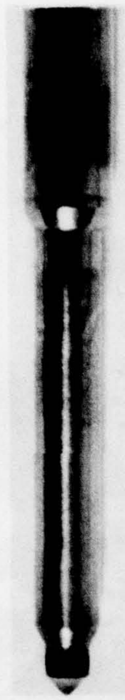


Cylinder 6

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

FUEL INJECTOR PINTLE

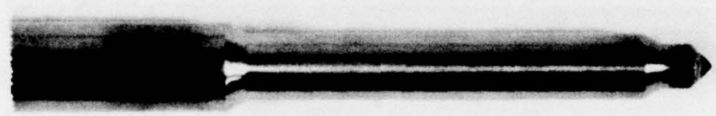


Cylinder 1

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

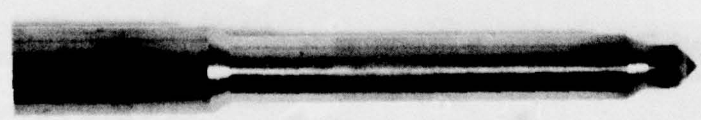
Engine: LDT-465-1C    Fuel: 10% Water-Emulsified DF    Lubricant: REO-103, Grade 30

FUEL INJECTOR PINTLE



350 to 420 Hours

Cylinder 2

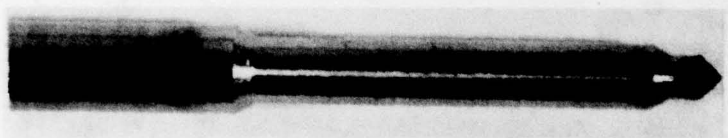


0 to 350 Hours

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

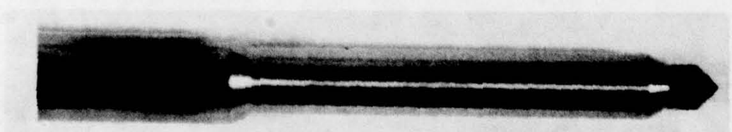
Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

FUEL INJECTOR PINTLE



350 to 420 Hours

Cylinder 3

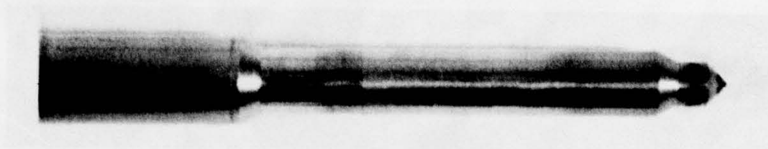


0 to 350 Hours

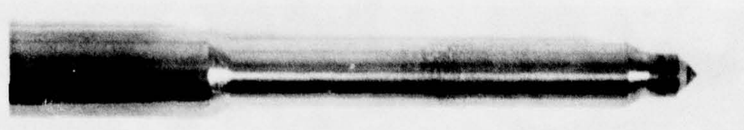
DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

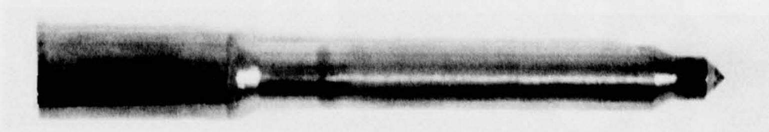
FUEL INJECTOR PINTLES



Cylinder 6



Cylinder 5



Cylinder 4

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

Cylinder 1 FUEL INJECTOR NOZZLE HOLE

OUTSIDE SURFACE

INSIDE SURFACE

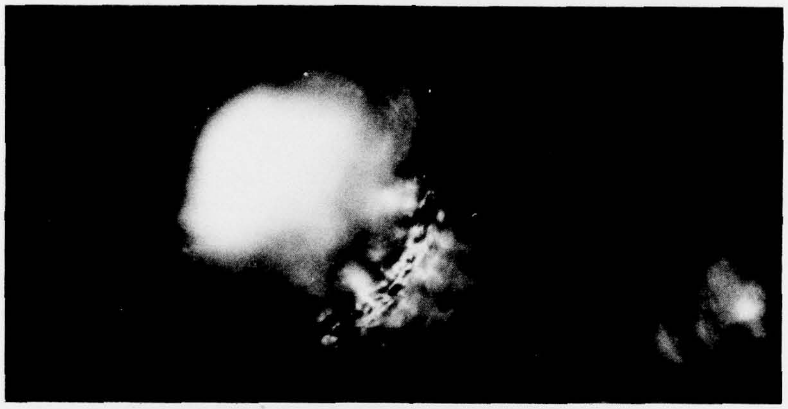
DEEP INSIDE SURFACE

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

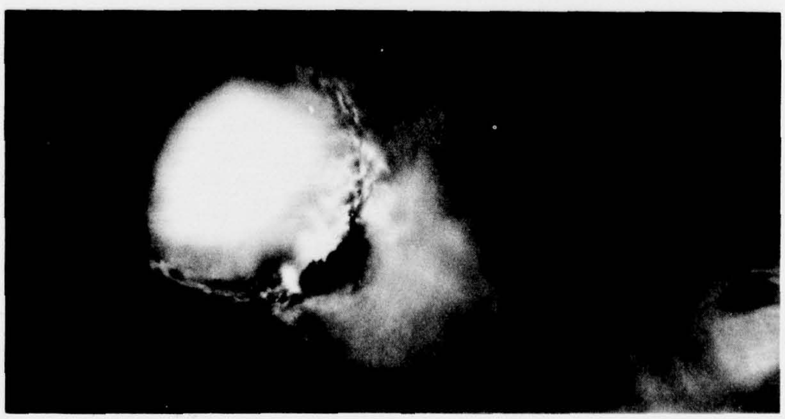
Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

Cylinder 2 FUEL INJECTOR NOZZLE HOLE

OUTSIDE SURFACE



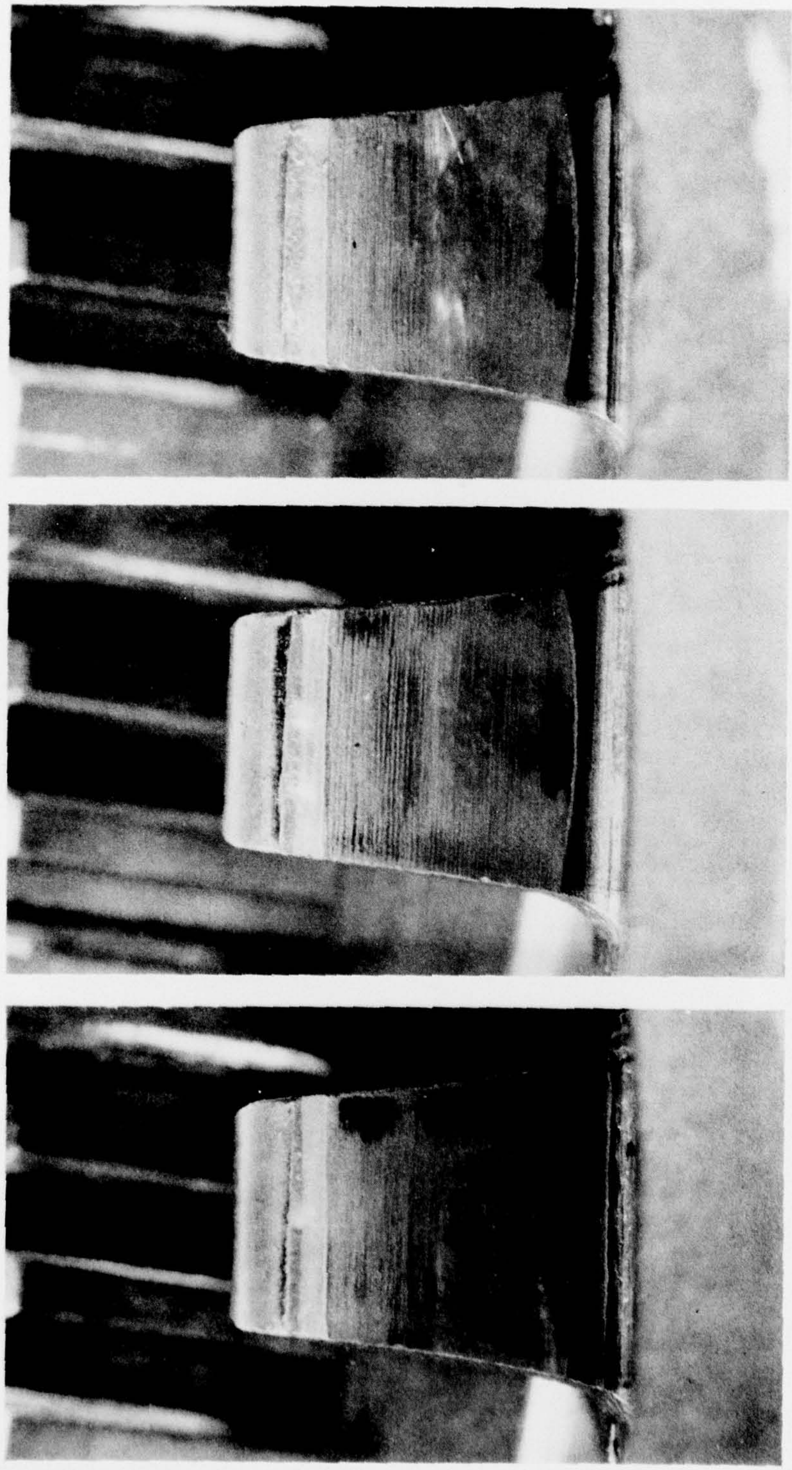
INSIDE SURFACE



DEEP INSIDE SURFACE

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

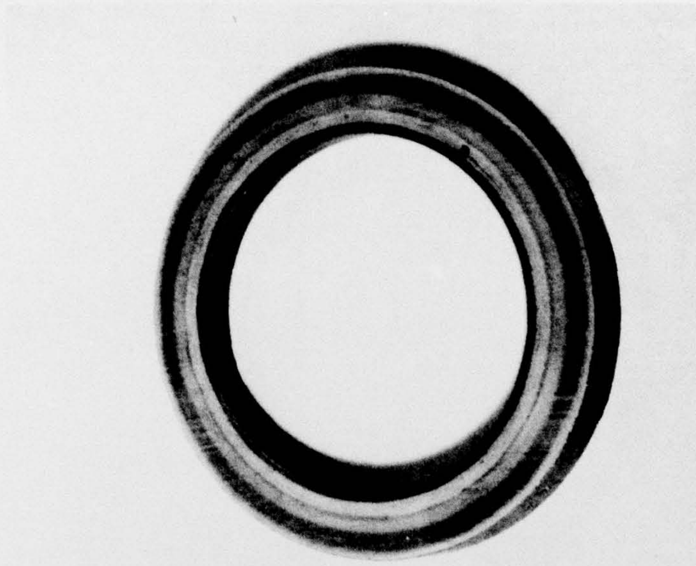
Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30

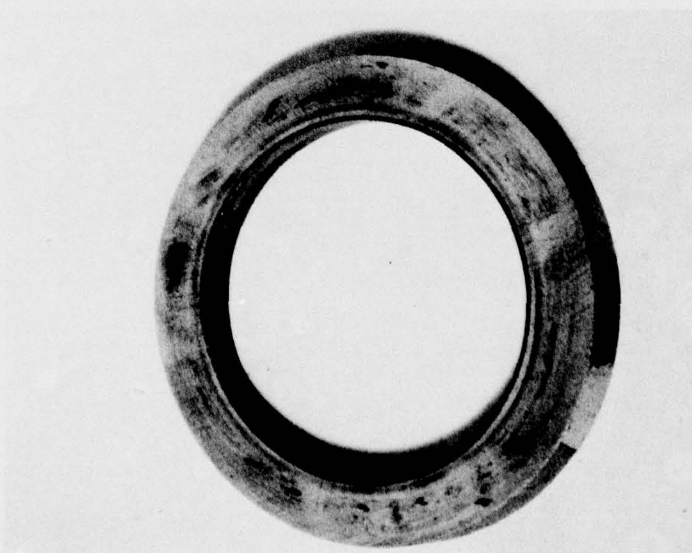


FUEL INJECTION PUMP ADVANCE WEIGHT FINGER

DOUBLE (420 Hour) WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: 10% Water-Emulsified DF Lubricant: REO-203, Grade 30





FUEL INJECTION PUMP ADVANCE CONTROL RING